MASTER OF SCIENCE

Exploring the benefits of a risk based approach to the management and resilience of infrastructure assets.

Thomson, Douglas Clark

Award date:
2017

EXPLORING THE BENEFITS OF A RISK BASED APPROACH TO THE MANAGEMENT AND RESILIENCE OF INFRASTRUCTURE ASSETS

by

Douglas Clark Thomson

A thesis submitted in fulfilment of the requirements
for the degree of Master of Science in the
Division of Civil Engineering of
the University of Dundee

October 2016

Table of Contents

List of Figures

List of Tables

Acknowledgements

For their continuous help and guidance, not to mention unending patience, throughout the preparation of this research, I would like to thank my supervisors: Malcolm Horner, Emeritus Professor of Engineering Management at the University of Dundee and Doctor Mohamed El-Haram, Senior Research Fellow in the Construction Management Research Unit, Division of Civil Engineering, at the University of Dundee. Their guidance and insight at critical points has been first class and I have relished the insight into the academic way of life which they have generously afforded to me. My rainbow may not be complete but the sky has still brightened for me as a result.

I would also like to thank the two bridge managers over the course of this study: Iain McKinnon and Alan Hutchison, for their supply of data, staff input for verification and helpful feedback on results.

My contacts at Halcrow CH2M have been generous with their time and attention so thank you Eddie McDowell and Nicola Vemmie. The supervisory team of Tim Broyd, Paul Conroy, David Pocock and Donald Bell were also instrumental in agreeing the frame of reference at the commencement of this work. I have leaned on the supporting work of Matthaios Paraskevopoulos and Reme Guienne. Support was also given by Tony Newell and Dominic McBennett of Scottish Water. The financial support of both the Engineering and Physical Sciences Research Council and Halcrow CH2M is gratefully acknowledged.

I would finally like to thank my family, for their unconditional support in this endeavour and my classmates and friends for their suggestions, support and comic relief between August 2010 and November 2013. This particularly includes the Scottish Construction Centre staff and students Ali Greig, Alan Tough, Doug Forbes, James Sutherland, Matthaios Paraskevopoulos, Reme Guienne, Ashley Rice and Anna Drogon.

Douglas Thomson

Dundee, 2016

Declaration

I hereby declare that this thesis has been compiled by me, that it is a record of work completed by me, all references cited have been consulted by me and that it has not previously been accepted for a higher degree at this University or any other institution of learning.

Douglas C Thomson

Certificate

This is to certify that Douglas Thomson has done this research under my supervision, and that he is qualified to submit for the degree of Master of Science.

Professor R.M.W. Horner

Emeritus Professor of Engineering Management

Abstract

The ***aim*** of this study is to explore the application of integrated logistics support (ILS) techniques to the design and management of resilient civil engineering infrastructure.

It is recognised that the fast developing discipline of asset management, with its adoption of ILS tools as one of a variety of techniques likely to be useful in enhancing the resilience of assets to service level failures, is a useful vehicle to disseminate these techniques. The main question to be addressed is whether ILS techniques can, when suitably adapted and applied, be of value in improving understanding and efficiency of resilient infrastructure design and maintenance regimes for infrastructure assets.

This has been tackled in three main stages:

Stage 1 of the research assesses the varying maturity of asset management planning across civil engineering infrastructure sectors. Important factors are found to be the attitude and nature of industry regulators and the degree of inter-company regulation.

Stage 2 is a direct comparison of two sectors in terms of their progress in implementation of asset management planning; roads and water. The water sector is further advanced than roads and features and reasons are listed in section 4.

Stage 3 is a detailed ILS application to a case study with a view to identifying and quantifying the added value, including resilience benefits.

The value of the exercise is judged against the 4 objectives below:

1/ To review asset management plans for different infrastructure sectors in order to understand a/ the extent to which risk based asset management is implemented and b/ to explore any difference in the maturity of asset management planning across different sectors. If differences are identified a secondary objective is to explore the reasons why.

2/ To determine whether the application of integrated logistics support (ILS) to infrastructure projects offers a practical tool within the risk based approach recommended in PAS 55.

3/ To compare the results of an FMECA analysis at a system and unit level of detail for the risk based assessment. To assess what level of detail is required for the structural breakdown system in order to allow an effective yet robust FMECA analysis to be carried out.

4/ To determine whether ILS can be applied efficiently to an assessment of the resilience of infrastructure assets.

Objectives 1,2 and 3 have been largely fulfilled, within the parameters of the data available, and bearing in mind the limitations of one case study. Objective 4 will require further monitoring of effectiveness over a longer time span.

1 Introduction and background

1.1 Introduction

Western societies have current concerns which will impact upon civil engineering infrastructure design, construction, maintenance and operation. These include carbon emission reduction programmes, budgetary restraints, adaptation measures to cope with predicted climate change, sustainability pressures, the need to ensure reliability and resilience for all essential infrastructure in the face of shock events with either natural or man-made causes. There are also on-going needs to avoid ‘bottlenecks’ in capacity which would adversely affect economic growth. Recent and on-going government led reports (Infrastructure Cost Review 2010; National Infrastructure Plan 2010 Government Construction Strategy 2011) are evidence of the importance currently accorded to these factors.

Adoption of whole life costing practices in order to put more emphasis on maintenance costs is being encouraged by government procurement through the private finance initiative (PFI) route (e.g. M74 design, build, finance and operate consortium in Appendix A1) Contracting organisations are having to price in operating and maintenance costs and compete on that basis. This competition should encourage wider collection of infrastructure cost and lifespan data and help to drive down whole life costs. The expansion of asset management planning across the UK is also motivated by the same drivers. Increasing efficiencies and interdependencies, however, also carry increasing risks of system failures arising due to unforeseen or non-routine events. System resilience threats increase accordingly and must be similarly considered.

Some current research programmes related to civil engineering infrastructure (resilientfutures.com and www.itrc.org.uk) are focused on the resilience of infrastructure and take account of the increasingly interconnected nature of infrastructure sectors. For example, the increasing use of telecommunications for monitoring the condition and operation of highway signage and water supply operations makes these networks vulnerable to cyber-attack. More extreme weather events, due to climate change, are forecast to put increasing strain on our national infrastructure and this, combined with public intolerance of network breakdowns, has led government and infrastructure operators to assess the weaknesses and risk factors inherent in their networks. Research is attempting to model some of the critical interconnections (NIAC 2009 and AEA 2010).

A UKWIR 2013 report 'Resilience Planning: Good Practice Guide' contrasts an over-arching 'top down' approach (for large and complex assets) to a 'bottom up' approach using ' a systematic analysis of the implications of a series of individual hazard events at critical assets that could trigger system failure'. Integrated Logistics Support (ILS) tools (refer to Glossary) are highlighted as an important methodology for a 'bottom up' approach and this study aims to establish some evidence of their utility in such applications.

1.2 Research objectives and background

The initial aim of this research was to interrogate the barriers and advantages associated with the application of ILS tools to civil engineering infrastructure, with a view to enhancing resilience. Given the increasing adoption of asset management practice throughout the industry and the inclusion of ILS as a suggested leading tool in the asset management toolbox of techniques, it was recognised early on that the asset management framework offered a useful vehicle to test and advance the application of ILS within the civil engineering industry.

Previous research work within the Construction Management Research Unit in the Civil Engineering Division at the University of Dundee has applied Integrated Logistics Support (ILS) techniques to cost effective maintenance strategies for buildings (Marenjak 2004, El-Haram & Horner 2002 and 2003). Much work has been done in order to a) tackle some of the barriers preventing wider application of the techniques in construction and b) establish the scale of potential financial savings. This study will proceed with similar aims, but in the infrastructure rather than the building sector.

This study is funded by both the Engineering and Physical Sciences Research Council and CH2M; CH2M also provided support in terms of input to the scope of the study, staff time, access to infrastructure operators, case studies and asset management data.

A 'problem formulation' meeting between CH2M directors, CH2M Scottish office staff and the research team from the University of Dundee formulated 3 preliminary work programmes.

1/ *Compiling maintenance strategies, needs and opportunities across the UK's 4 primary infrastructure sectors:* water, energy, transport, communications.

2/ *Comparing risk-based asset management decision-making between the water and highways sectors.* Following on from Task 1 above, asset management practices between these two sectors will be contrasted by studying current Scottish Water and Transport Scotland practice.

3/ *Development (process and criteria) of resilience and cost effective asset management of existing strategic assets.* This work will use ILS tools to assess the resilience of a sample section of infrastructure; the Tay Road Bridge.

The three main strands of the research, described as stages 1, 2 and 3 in this study, are envisaged to be linked diagrammatically as shown in Figure 1. This shows the 4 main physical infrastructure sectors surmounted by the ILS investigative tools, flanked by the main topic of system resilience and its constraining counterpart of cost efficiency and all included within the embrace of the developing discipline of asset management whose potential for increasing the quality of decision making is the driver for better data collection and management, which is key to supporting the use of ILS. Double headed arrows identify the 2 way links between the bodies of knowledge.

The objectives of this research were then developed as:

1/ To review asset management plans for different infrastructure sectors in order to understand a/ the extent to which risk based asset management is implemented and b/ to explore any difference in the maturity of asset management planning across different sectors. If differences are identified a secondary objective is to explore the reasons why.

2/ To determine whether the application of integrated logistics support (ILS) to infrastructure projects offers a practical tool within the risk based approach recommended in PAS 55.

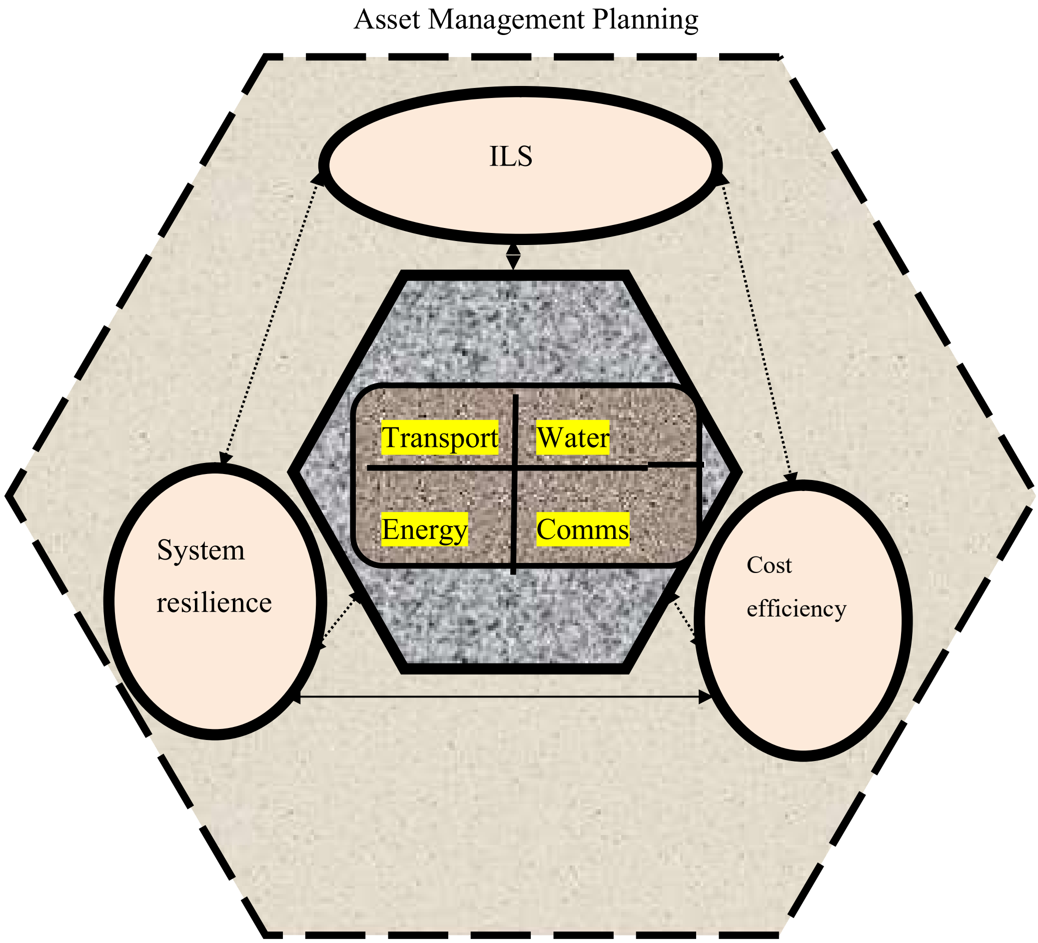


Figure 1 Project connections

3/ To compare the results of an FMECA analysis at a system and unit level of detail for the risk based assessment. To assess what level of detail is required for the structural breakdown system in order to allow a sufficiently robust FMECA analysis to be carried out.

4/ To determine whether ILS can be applied efficiently to an assessment of the resilience of infrastructure assets.

Stages 1 and 2 form the basis of fulfilling objective 1. Objectives 2, 3 and 4 are considered in stage 3.

1.3 Layout of the Thesis

The study was undertaken in three stages.

1/ *Comparing maintenance strategies, needs and opportunities across the UK's 4 primary infrastructure sectors:* water, energy, transport, communications.

a/ This took the form of a literature search to record and compare UK asset owner practice in each sector. Reference was made to leading UK and international guidance documents.

b/ Comparative sector progress in compiling and operating effective asset management plans was recorded. Approaches towards incorporating the need for resilience in maintenance strategies were examined. Use was made of CH2M project experience and access to guidance documents and operations staff where appropriate.

c/ The extent of any current ILS adoption was recorded.

2/ *Comparing risk-based asset management decision-making between the water and highways sectors.*

Task 1 above allowed asset management practices between these two sectors to be contrasted. Attention at this stage focussed on Scottish Water and Transport Scotland highways practice, utilising case studies and examples.

3/ *Development (process and criteria) of resilient and cost effective asset management of existing strategic assets.*

i) ILS was introduced at this stage by modelling a trial section of infrastructure in terms of functionality and service levels and then applying failure modes, effects and criticality analysis (FMECA) and reliability centred maintenance (RCM) in order to test resilience against projected natural and accidental threats. The threat levels varied by failure mode and by consideration of the recovery effort required in the event of such a failure. The modelling is analytical but the ILS applications are essentially qualitative albeit numerical assessments.

ii) FMECA and RCM toolkits were tailored for this application but also with a view to future applicability for other infrastructure resilience audits.

iii) The verification of the ILS results required expert input from bridge operations staff and this was co-ordinated by the University research team. The review panel considered the critical network areas, anticipated threats to service levels, and other factors affecting the resilience of the infrastructure networks.

iv) An example of a possible solution to a vulnerability was costed and tabled for engineering assessment.

A 7 stage process was applied at stage 3 as below. This is based on a combination of industry standard guidance for the application of Integrated Logistics Tools, plus the previous modelling undertaken in the reference in number 3.

1/ Define the boundaries of the asset so it is clear which physical limits we are working within.

2/ Define the level, stage and scale of assessment to be applied to the example or project. e.g. conceptual, design, construction, operation, demolition. This will depend on the stage of the project and the level of available detail. Establish standards of service levels and business consequences of temporary failure to meet these.

3/ Construct a functional/physical model (ref mil-std-1629A & Elharam & Horner 2002). This should include interconnections with supporting systems.

4/ Define the type and scale of threat envisaged, using climate predictions and scenario planning.

5/ Establish an expert review panel. Undertake a threat and vulnerability study (business impact analysis), using FMEA structure and format, to list and quantify failure mechanisms, locations and consequences.

6/ Undertake a criticality analysis to prioritise vulnerabilities based on failure consequences. A common measurement scale will be required to allow trade-offs between consequences in different business areas e.g. between environmental and reputational damage.

7/ Investigate protective solutions. These could range from retrospectively applied physical refurbishments, increased security controls, future specification enhancements, provision of redundant links or spare equipment held in reserve.

The rest of this document is laid out as below:

1/ Chapter 2: The literature review tackles infrastructures, resilience, asset management and integrated logistics support. Also included are data collections for the 3 work stages.

2/ Chapter 3: Methodology includes the detailed steps included in all 3 stages.

3/ Chapter 4 sets out all the results

4/ Chapter 5 lists conclusions and recommendations

2 Literature Review

2.1 Civil engineering infrastructures

2.1.1 Definition and classification

"Infrastructure can be succinctly described as the systems and organisations required for the function of a society" (Attoh-Okine 2009). As shown in table 1 below, this is a little too wide ranging for the purposes of this research. The International Infrastructure Management Manual 2002 goes further in defining infrastructure assets as "Stationary systems forming a network and serving whole communities, where the system as a whole is intended to be maintained indefinitely at a particular level of service potential by the continuing replacement and refurbishment of its components." This is a definition specifically formulated to suit an asset management approach as it emphasises permanence and the provision of service.

Academic papers often refer to critical infrastructure(s) which Utne et al (2011) define as "technological networks, such as energy supply, transport services, water supply, oil and gas supply, banking and finance, and ICT (information and communication technology) systems." 'Critical' is used in the sense that the system is fundamental to civilised human urban existence although it can also be used to define the most important elements of the systems i.e. those which need particular protection or attention to ensure resilience.

Other, mainly government publications, address varying scopes when they mention infrastructures, depending on which issues they are tackling and which professions are defining the scope. These are summarised in table 1 below:

The United States (NIAC 2009) recognise 19 critical infrastructure and key resource sectors. Their use of the term 'critical' is largely guided by the risk of terrorist threat following the attacks on the twin towers in New York and appears to mean 'of national importance'. Not all of these are physical networks or systems.

Table 1 Infrastructure sectors

Utne et Al 2011	NIAC 2009	National risk register 2010	UK infrastructure group 2010	UK national infrastructure plan 2011	Council for science and technology 2009
Energy supply	Energy	Energy	Energy	Energy-electricity, gas	Energy
Transport services	Transportation systems	Transport	Transport	Transport- roads, rail, airports, ports	Transport
Water supply	Drinking water and other treatment systems	Water	Water	Environment- water and sewerage, flood risk management, waste	Water
ICT	Communications	Communications	Communications	Communications	Communications
Banking and finance	Banking and finance	Finance			
Oil and gas supply	Chemical				
	Agriculture and food	Food			
	Public health and healthcare	Health			
	Commercial facilities				
	Critical manufacturing				
	Dams				
	Defense industrial base				
	Emergency services	Emergency service			
	Government facilities	Government			
	Information technology				
	National monuments and icons				
	Nuclear reactors				
	Materials and wast		Waste	Incl in environment	
	Postal and shipping				

The UK government has identified nine national infrastructure sectors which require protection against hazards or attack (National Risk register of Civil Emergencies 2010 edition). The UK Infrastructure Group counts 5 civil engineering infrastructure sectors. The UK National Infrastructure Plan 2011 lists 10 infrastructure networks. These are then grouped into 4 larger sectors.

The Council for Science and Technology (2009) define 4 national infrastructures to focus on; communications, energy, transport and water. These are the four national infrastructures with significant fixed civil engineering systems or networks. Because they are replicated across the other reports, this research will work with these classifications. Section 4 of this report further sub-divides these when reporting asset management progress.

Now we have our infrastructures, why are they important?

"Investing in infrastructure, ……. is vital to the UK's economic growth. High quality infrastructure increases productivity, lowers production costs and raises output. It also enables a skilled and healthy workforce and improved public services delivery, all of which are essential for the UK to remain competitive." (CBI, Building strong foundations 2011).

The National Security Strategy (NSS) sets out that a key task is to improve resilience of the infrastructure most critical to keeping the country running against attack, damage or destruction (Cabinet Office: Natural Hazards and Infrastructure 2011).

The Infrastructure Cost Review main report 2010 states "The Government's National Infrastructure Plan 2010, published in October, describes planned investment in infrastructure of £200 billion over the next 5 years. Between £15 billion and £20 billion will be spent each year directly on renewals and capacity enhancement projects and programmes – principally civil engineering works. The ability to deliver infrastructure investment priorities efficiently and effectively is crucial to achieving the UK"s growth objectives. "

"Good asset management strategies have the potential to decrease costs through minimising unplanned or unnecessary interventions" is cited as one way to help achieve efficiency savings of up to 15%, by increasing resilience and reducing unplanned maintenance expenditure (Infrastructure Cost Review July 2014).

Table 2.

Examples of infrastructure assets (Table 1.1 from CIRIA Report C677, 2009)

Industry sector	Examples of assets
Electricity utilities	towers, transmission lines, transformer stations
Flood defences	embankments, barriers, coastal defences
Gas utilities	pipelines, gas holders (or gasometers), distribution centres
Highways	roads, bridges, tunnels, earthworks
Ports and harbours	docking berths, hardstandings, breakwaters
Rail	tunnels, bridges, earthworks, escalators, large buildings such as stations
Water utilities	water mains, sewers, sewage treatment works
Other civil engineering structures	waste management facilities, dams, reservoirs

2.1.2 Interdependencies and vulnerabilities

As physical infrastructures become more refined, particularly with more sophisticated control arrangements in order to either avoid or minimise more expensive renewal or expansion, this creates connections between systems. An example is the increased usage of driver advice signposting on motorways which creates connections between communications, electrical and transport systems.

These interconnections create dependencies between networks which have the potential to create a 'domino effect' i.e. a breakdown or rupture in one network has the potential to disable a dependent or interdependent network. Rinaldi et al (2001) identify 3 drivers towards the increased prevalence of interdependencies in the United States: the increasing use of IT, shedding of excess capacity following deregulation of sectors, and company mergers reducing redundancy and overheads. Understanding these interdependencies and installing redundancies (spare capacity) or 'firebreaks' must be an important factor in ensuring resilience by setting boundaries to damage resulting from a destructive event.

There is progress among researchers in modelling interconnections between parallel networks and work has been done in analysing what level of damage can be sustained before functionality is destroyed. This is also addressed and summarised in the Cabinet Office paper Natural Hazards and Infrastructure of March 2011.

An early paper (Rinaldi et al 2001) analyses networks and interconnections and frames modelling challenges which spawn later papers. Much of the categorisation and terminology (see Figure 2) has been taken up by later authors using mathematical models and statistical tools.

Rinaldi introduces the fundamental concept of infrastructures as complex adaptive systems. This allows resilience to have more than a 'bounce back' dimension. In terms of interdependencies, 4 classes are identified: physical, cyber, geographic and logical. A definition of inter-dependency is proposed: "A bidirectional relationship between two infrastructures through which the state of each infrastructure influences or is correlated to the state of the other". A dependency is where the relationship is unidirectional. Examples of interdependencies are shown in Figure 3.

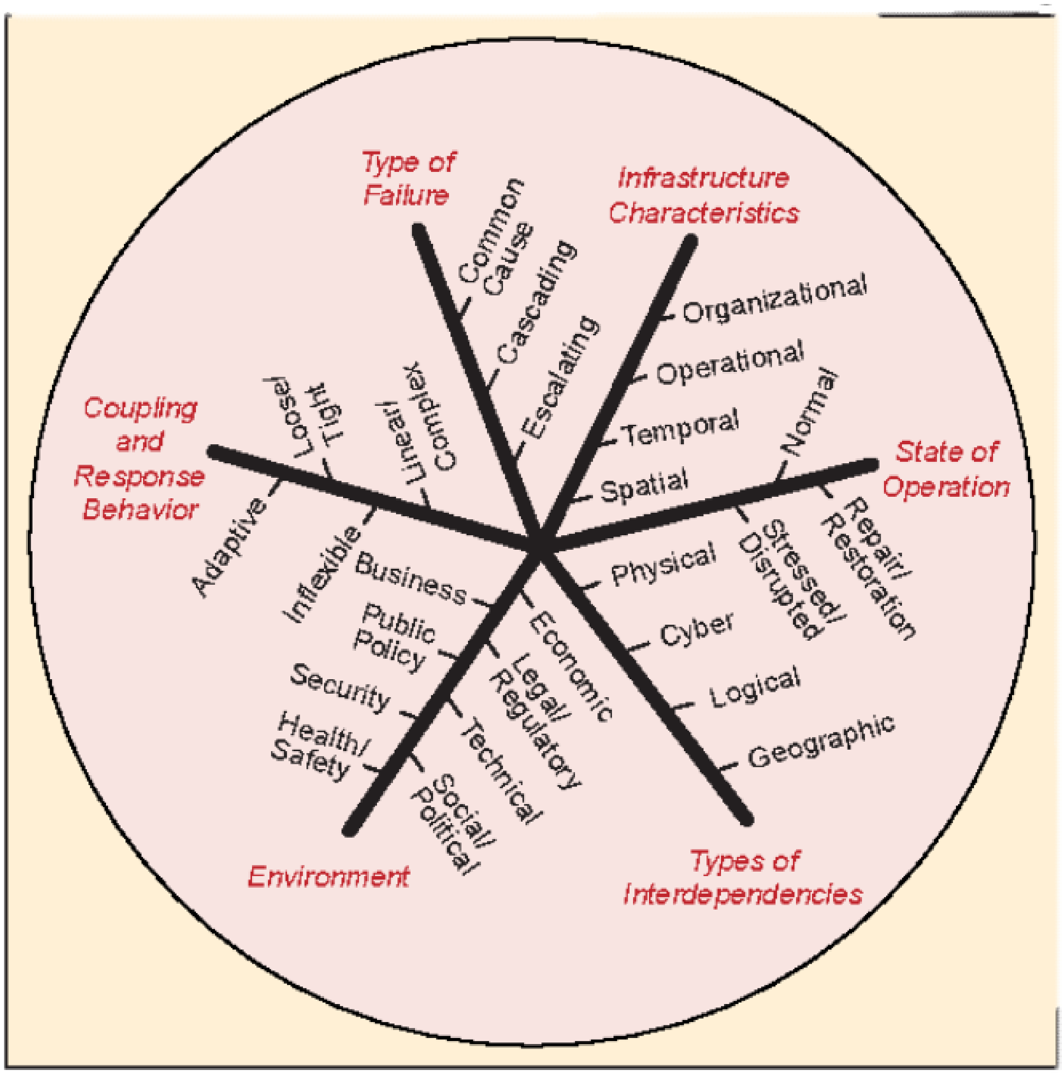


Figure 2 Infrastructure categories (Rinaldi et al (2001) fig 1)

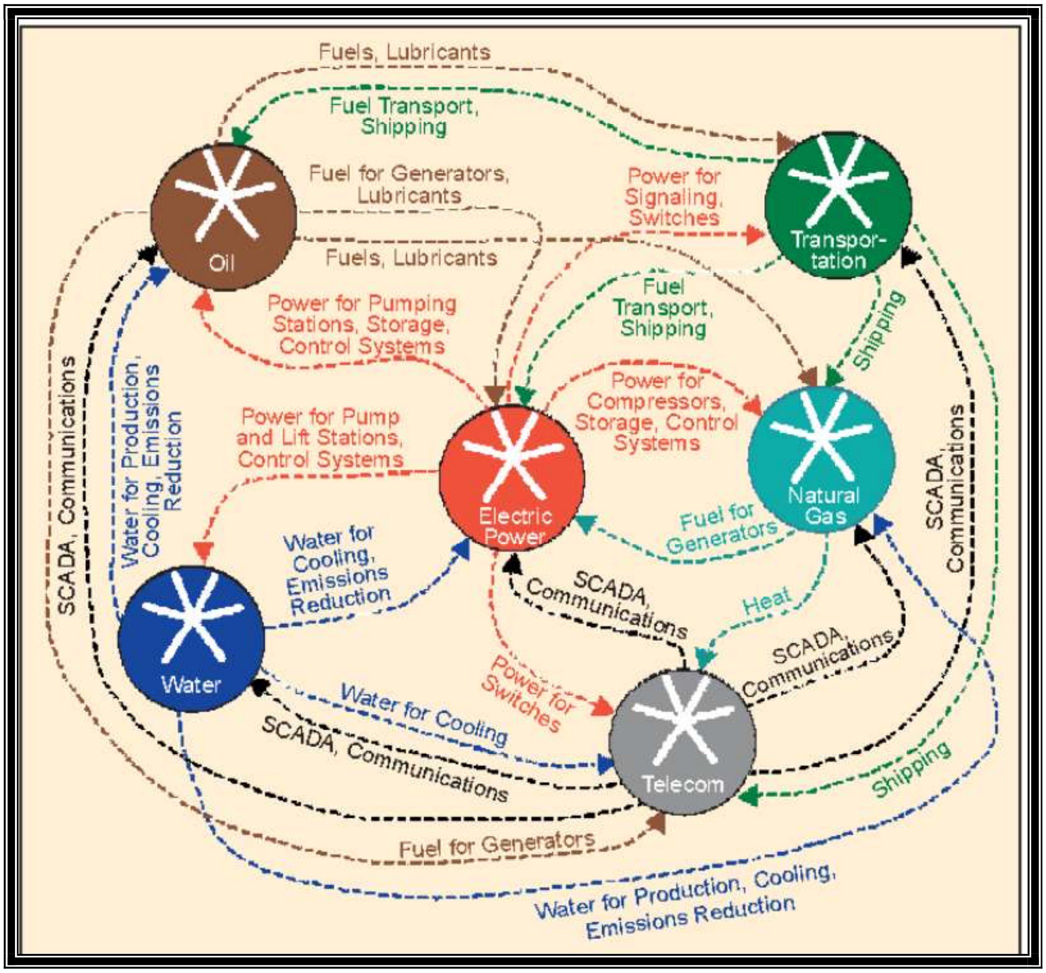


Figure 3 Infrastructure interdependencies (Rinaldi et al (2001) fig 3)

Further useful classification terminology from Rinaldi et al (2001) is the spatial scale extended from Perrow's taxonomy (see the glossary).

Examples of attempts to model interdependencies mathematically with a view to quantifying vulnerabilities and hence resilience can be seen in papers by Attoh-Okine et al (2009) and Utne et al (2011).

Utne et al use Johansson and Jonsson's identification of "two types of approaches for dependency modelling/analysis - empirical and predictive approaches". Their paper uses an empirical 'risk and vulnerability analysis' together with cascade diagrams to investigate actual incidents and quantify the resulting risks arising 'downstream' of the incident. The empirical approach has the advantage of simplicity for practitioners, lends itself to the use of ILS techniques in analysis and is more in line with the approach favoured by Scottish Government resilience forums (Scottish Government CNI group 2011).

Attoh-Okine et al (2009) attempt to formulate a resilience index, starting from an index derived through earthquake engineering and using ‘belief function frameworks’ to cope with the usual practical situation where failure and event data is incomplete and subject to change with time. It depends upon expert engineering input to quantify essential factors, as would any over-arching methodology seeking a practical application. The hypothesis of this current MSc thesis is that ILS techniques can be used to marshal that expert input – i.e. that ILS can provide the essential ‘bottom up’ input to best utilise a modelling methodology.

In terms of differentiating between the characteristics of national infrastructures, an important observation is made in the Natural Hazards and Infrastructure (2011) report between the network design standards of the electricity transmission and distribution networks (very effective in their ability to prevent disruption) and the lack of ‘freeboard capacity’ in the water and transport networks, due to the far higher costs of providing redundancy therein.

One especially relevant feature of increasingly complex interdependent networks is their propensity to fail quickly with little warning (Ferguson 2011). If physical infrastructures are to become increasingly complex to the extent that they mimic natural, economic and political systems then an accompanying characteristic is the risk that they become non-deterministic and fail in an unpredictable fashion. This is exactly the most catastrophic failure type which a resilience analysis must guard against.

2.2 Resilience

2.2.1 Definition and contemporary importance

“The concept of resilience is central to any systematic approach for protecting the nation’s critical infrastructure systems from both natural disasters and intentional acts” (Willingham 2008). Definitions of resilience have been formulated by a range of authors writing in this field. Early definitions came from the biological use of the term, i.e. a measure of the ability of plant life to endure in the face of external attack. Attoh-Okine et al, (2009) quotes Holling’s definition “resilience determines the persistence of relationships within a system and is a measure of the ability of these systems to absorb change state variable, driving variables, and parameters and still persist”. The term can also be used in a sociological and economic context and Dawley et al (2010) apply it to peripheral geographic areas in terms of their ability to withstand economic shocks. This brings out the ‘adaptive capacity’ strand of resilient behaviour i.e. an ‘elastic bounce’ is not the only type of recovery. Resilience engineering is an emergent academic discipline (Hollnagel 2006) although it has strong links to reliability and safety engineering. This research is concerned solely with improving resilience of civil engineering infrastructure, where definitions have been formulated in both academic and government publications. Most of these have two aspects; protection against failure and recovery after failure.

One of the most succinct is attributed to the 17th century French poet Jean de La Fontaine (Willingham 2008) “I bend but do not break”. This captures the ‘bounce back’ nature of resilience but only relating to personal performance under pressure. “the ability of the community, services, area or infrastructure to withstand the consequences of an incident” is quoted by the Pitt Report in 2008. This again captures the broadly understood gist of the term but a more precise and focussed definition is required for current purposes.

A more fulsome attempt is made (Allenby and Fink, 2005) with ”the capacity of infrastructure, service and social systems potentially exposed to hazards from technical, natural or intentional events to adapt either by resisting system degradation or by readily restoring and maintaining acceptable levels of functioning, structure and service following an event" This introduces aspects of the threats which must be combated (hazards from technical, natural or intentional events), the elements of restored service (functioning, structure and service), and the twin resilience functions of protection (resisting system degradation) and recovery (restoring and maintaining). It is probably too wide ranging for use here as it includes 'service and social systems' which we are not concerned with. "The ability of a network to defend against and maintain an acceptable level of service in the presence of challenges" is stated by Smith et al (2011) and has the advantage of including the concept of service levels; an important aspect of performance measurement in relation to infrastructure networks. Smith et al (2011) go on to attempt to model the risk exposure which challenges resilience as a multiple of 3 aspects: the probability of a challenge occurring, the probability of that challenge causing failure and the impact (consequences) of a failure. This sets up a priority list against which resilience measures can be put in place.

Rosenkrantz et al (2009), in common with others working in the field, use model networks of nodes and links to investigate how many nodes and links can be destroyed before service is affected. This allows them to use redundancy (i.e. duplicated or spare nodes and links) to increase resilience. This is unlikely to be cost effective for civil engineering aspects of infrastructure systems where spares provision (being more expensive than small tele/electrical items) is likely to only be part of the answer. These models are generally based on electrical and telecom networks. Notions of service oriented networks, node resilience, service continuation despite damage, and graphical representation of resilience have application potential for civil engineering.

Ridley (2011) looks at adding resilience as a strand of existing corporate social responsibilities (CSR) of companies. The argument is that the understanding of the relationship between government and businesses already inherent in a corporate social responsibility approach could be put to use in analysing the resilience of infrastructure. This is interesting in the context that much of the civil engineering infrastructure in the UK (and US) is run by private companies (OFT 2010 report). Depending on the regulatory method there may or may not be a direct route to apply pressure on these companies to ensure a resilient service. While loss of reputation is a major consequence of service failure (Yorkshire Water supply shortfalls in 1996 drought, Northern Ireland water supply shortfalls in 2010, Highway winter protection problems in 2010 in Scotland), the need to report resilience as part of the CSR duties would increase its priority. Ridley's paper includes no analysis of examples of this claimed benefit however.

This issue of the market value of resilience is picked up by Collins, (2011), who recognises "Unless the market puts a value on resilience under extreme conditions it is unlikely that any unregulated operator will invest in a capability to provide it, and a regulated one will only do so if instructed". Collins also gives an overall background as to why system resilience is important; because "their operation is now very highly optimised, tightly scheduled and modally interdependent". "Awareness by the general public of vulnerabilities in the national infrastructure is low, but reactions are swift and often heated when things go wrong" (Council for Science and Technology 2009).

The double functions of protection and recovery are continued with a 4 part UK government breakdown of the term (Cabinet Office: Natural Hazards and Infrastructure 2011). Figure 4, taken from the report, is shown below:

Figure 4 Features of Resilience (Cabinet Office: Natural Hazards and Infrastructure 2011)

The resistance and reliability elements are essentially concerned with protection against a known range of events, generally specified to an 'expected' standard. Response and recovery, plus redundancy allow consideration of behaviour following failure arising out of an extreme event. It is possible to regard redundancy as part of the protection group, but only if the replacement functional service operates after failure of a part and before failure of asset service levels. For our purposes the 4 elements may be considered separately. The bulk of the Cabinet Office guide goes on to examine elements of figure 3 in their report, repeated in Figure 5 below.

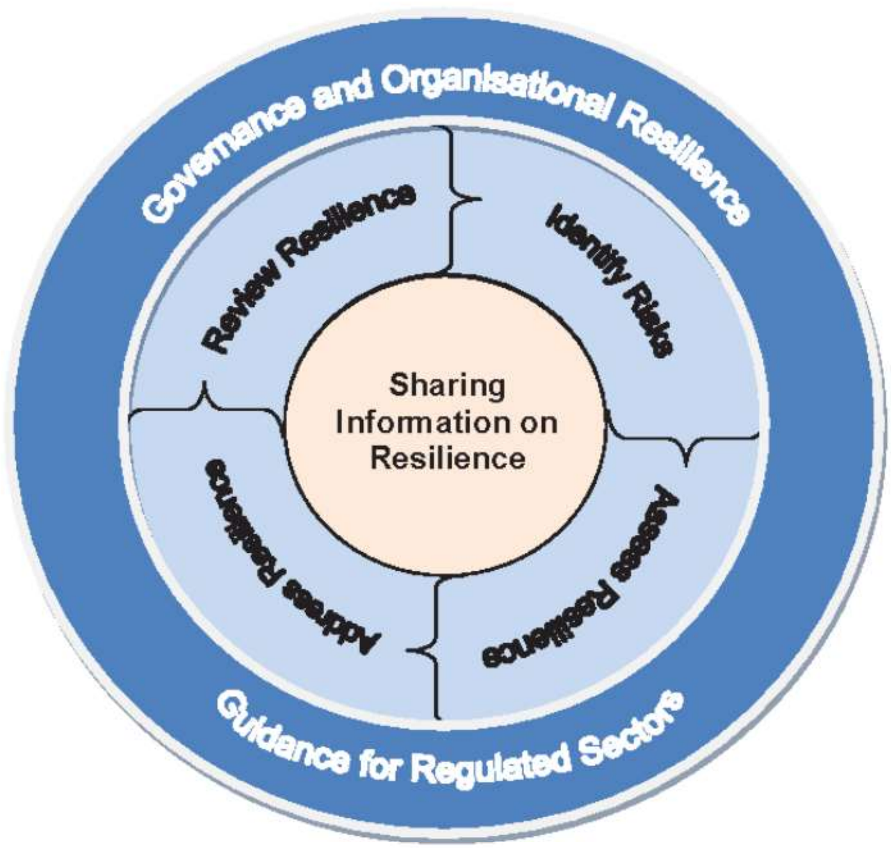


Figure 5 Sharing Information on Resilience (Cabinet Office: Natural Hazards and Infrastructure 2011)

Most of the guide examines organisational methods of bringing people together to identify vulnerabilities and tackle resilience. Improving security against progressive failure, in particular, is the principal aim. Interdependencies must be understood with the aim of avoiding a domino effect.

In contrast, the NIAC report of 2009 removes protection from a resilience definition thus: "Infrastructure resilience is the ability to reduce the magnitude and/or duration of disruptive events. The effectiveness of a resilient infrastructure or enterprise depends upon its ability to anticipate, absorb, adapt to and/or rapidly recover from a potentially disruptive event."

One further feature of resilience is that it is necessarily threat specific i.e. the nature and scale of the threat must be known or decided upon before any resilience engineering is undertaken or assessed. A system which is resilient against a 1 in 200 year flood event may be anything but in the eventuality of a 1 in 300 year flood.

Looking at system resilience from an engineering designer viewpoint; the need for cost effectiveness guides us towards ensuring that protection against high probability events is managed by adherence to a design specification. Society must take a view on whether specifications cover low probability, high consequence events and in many cases (e.g. flooding of nuclear reactors), protection will be designed in. As it is generally not cost effective to design protection against low probability events the system will normally be designed to fail in these circumstances. It is this functional failure that the response and recovery element (figure 4) of resilience must seek to mitigate. This has two measurable dimensions; impact and duration.

These two aspects are treated slightly differently elsewhere (Vugrin et al 2011) as systemic impact and total recovery effort. This recognises that the effectiveness of the effort put in after a disruptive event can control the duration of the consequent lack of service. These two metrics are defined, graphically illustrated and used to cost different recovery strategies. Vugrin includes a definition of resilience thus "Given the occurrence of a particular disruptive event (or set of events), the resilience of a system to that event (or events) is the ability to reduce efficiently both the magnitude and duration of the deviation from targeted system performance levels". This ignores the 'protection' element of resilience but recognises the two elements of 'deviation' and ties resilience firmly to specific events. One improvement might be to substitute 'service levels' for 'performance levels'.

Willingham usefully recognises that failure protection is usually focussed on "high probability events" with a range of consequences between high and low scale damage. From a designer viewpoint the inclusion of 'protection' in a definition of resilience is potentially problematical as a standard specification ought to protect against high probability events.

Cabinet Office: Natural hazards and Infrastructure (2011) states that “resilience of infrastructure is provided through (a) good design of the network and systems to ensure it has the necessary resistance, reliability and redundancy (spare capacity), and (b) by establishing good organisational resilience to provide the ability, capacity and capability to respond and recover from disruptive events. The latter is gained through business operations and appropriate support for business continuity management.” This definition usefully reminds us that organisational improvements are as important as engineering ones and, indeed, ILS can be applied to processes as well as physical assets.

In essence then, normal design standards should cover protection against failure by high probability events. Resilient design needs to concern itself with the effects of failure following low probability events (prioritising the high impact end of the range). The ILS exercise will need to consider failure modes (how will it fail?) plus how to minimise magnitude and duration of the deviation from required service levels.

This research will primarily investigate the recovery aspect, (i.e. the NIAC approach). This research will also emphasise the physical engineering aspects or features rather than the (equally important) communication, management arrangements and emergency services organisational aspects, both because ILS is better suited to these types of solutions and because organisational arrangements are already being tackled by governments (e.g. the Scottish government’s resilience committee). Both these boundary conditions (recovery aspect plus physical engineering aspects) lead to the selection of Vugrin’s definition as being the most relevant and useful, albeit with the substitution of service levels rather than performance levels.

“Given the occurrence of a particular disruptive event (or set of events), the resilience of a system to that event (or events) is the ability to reduce efficiently both the magnitude and duration of the deviation from targeted system service levels” is this author’s preferred definition of resilience and is included in the glossary.

Vugrin also categorises system features which are affected by resilience enhancements. These are absorptive capacity, adaptive capacity and restorative capacity and these offer at least the prospect of a qualitative framework to compare events and resilient responses. Resilient infrastructure is a high priority for western governments. An appreciation of the critical level of support to society, complex interdependencies between systems and the vulnerability to external threats combine to require action at the top level. The NIAC (2009) report, for example, recommends "The White House should leverage its authority and leadership on resilience to coordinate and adjudicate conflict among regulatory agencies and actions in each sector to support the established resilience goals".

The UK government is similarly focussed with its Critical Infrastructure Resilience Programme, National Resilience Extranet and the consultation paper 'Natural Hazards and Infrastructure' of March 2011. This is supplemented by direct guidance to the regulated utilities in the 'Interim Guidance to the Economic Regulated Sectors' on how to build and maintain resilience. Much activity is also underway between emergency organisations, utility companies and local government in terms of information exchange, policy development and mock emergency exercises. The Scottish Government, for example, has published a 'Secure and Resilient' report in 2011 which demonstrates much liaison activity. Much of the detail is necessarily restricted to limited circulation but the approach is to set up committees and communication networks involving utility representatives for example, rather than to draw together and record sensitive data about infrastructure which is particularly vulnerable.

2.2.2 Threats

Against what threats must infrastructures be made resilient? As mentioned in section 2.2.1, any attempt to measure resilience can only be made in relation to foreseen threats. These threats can be classified into natural and man-made hazards. The aim of this section is to propose boundaries to the list and magnitude of threats to be considered.

Natural threats can be listed as: earthquake, tsunami, landslide, volcano, tornado, hurricane, tidal surge, fluvial flooding, fire, environmentally driven chemical or biological deterioration, drought, freeze, snow and ice, monsoon or heavy rain, longer term climate change risks. Man made threats can include nuclear explosion or radiation, bomb, war damage, traffic accident, environmental or process problem, consequences of economic shocks, longer term change of societal need, cyber-attack, civil disobedience, acts of deliberate aggression, chemical or biological deliberate attack and lack of maintenance. There can also be collateral damage from adjacent structures arising out of either natural or man-made causes.

Resilient design efforts can still improve the recovery capability of a failed system following the impact of an unforeseen event but it would be unclear how cost effective any measures might be if we do not have a magnitude and probability of event to measure against. In other words, the benefit could not be quantitatively assessed.

The UK National Security Strategy and Strategic Defence and Security Review identifies international terrorism, cyber-attacks, major accidents and natural hazards as the four most serious risks. Of these four, detailed consideration of cyber-attacks would require information technology expertise which is beyond the capability of this researcher. In addition, UK readiness to deal with acts of terrorism is necessarily restricted in terms of open access to information so this would not allow in depth research either. This resilience assessment of threats to particular sections of infrastructure will therefore consider in detail only natural and accidental damage.

The UK government (National Risk Assessment Team run from the Cabinet Office) has undertaken a national risk assessment to select the likelihood and potential impact of threats on a national scale (National Risk register 2010). These are shown graphically in figure 6 below.

Both axes measure increases in the arrowed direction. Only major risks operating to a national scale are included i.e. those which require a co-ordinated response by central government, hence the low likelihood of a transport accident requiring a national response, for example. The likelihood is based on an expert assessment of historical, statistical and scientific data, albeit the results do seem to give high consideration to terrorist attack. The impact is measured in terms of fatalities, personal illness or injuries, social disruption, economic damage and psychological impact in terms of disruption to behavioural patterns. In terms of impact upon infrastructure the Centre for the Protection of National Infrastructure (CPNI) is the relevant responsible body.

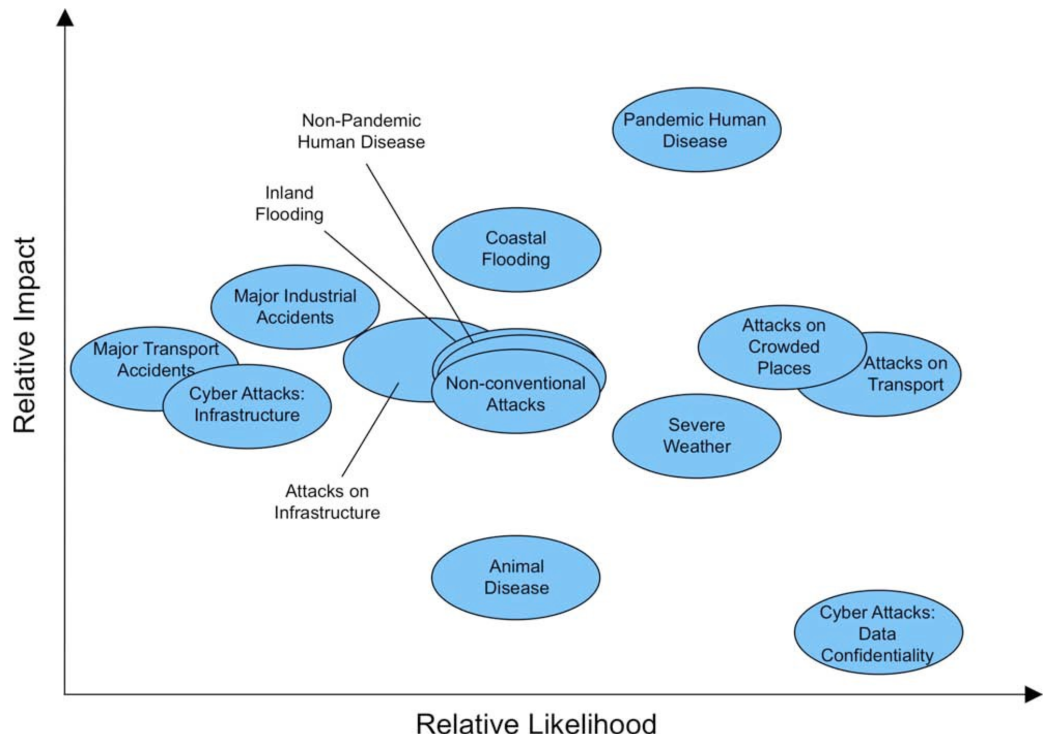


Figure 6, Nationally Significant Risks (National Risk register 2010)

Suggested threat levels for natural hazards (only) to be guarded against is listed in the UK discussion paper (Cabinet Office: Natural Hazards and Infrastructure 2011). These are proposed as ‘reasonable worst case scenarios’ for the purpose of eliciting feedback and summarised in Table 3:

There is little background evidence in the discussion paper for arriving at these proposed levels. They were derived by the Cabinet Office National Risk Assessment Team in conjunction with the Met Office, Environment Agency and the British Geological Survey and they appear to correspond to specification standards which should be protected against, rather than abnormal threats which a resilience exercise would measure recovery abilities against. Some amendments are likely, at least, in order to take account of geographic climate variability across the UK (e.g. wind speed limits look low when wind speeds in excess of 100 miles per hour were recorded at the Tay road bridge in the first half of December 2011).

Table 3 UK proposed threat levels

Inland Flooding	1 in 200 year event
Coastal Flooding	Coastal defences breached over a wide area
Wind Storm	For at least 6 hours, mean speeds 70 mph and gusts to 85mph
Cold	Snowfall for 7 days, depth of 30cm and daily mean temperature of minus 3 degrees centigrade
Heat	For at least 5 days, max temperatures of 32 and no lower than 15 degrees centigrade.
Dry	Periodic water supply interruptions for 10 months. Emergency drought orders in place.
Volcanic Ash	Entire UK mainland affected for 10 days
Severe Space Weather	Duration to be decided. (Assume equivalent to volcanic ash meanwhile – author insert)
Geological Threats	Relevant factors listed

Some cognizance of the consequences of failure also needs recognition when setting threat levels as a bridge’s failure to allow the passage of high sided vehicles requires much less recovery effort than the prospect of physical bridge damage. In effect there needs to be varying thresholds married against failure consequences, and checked against regional weather extremes, ideally on a whole life cost basis. In the meantime, they are a current guide as to the cost effective limits which the UK government consider reasonable to consider the resilience of civil engineering infrastructure against.

These levels of threat are a snapshot of contemporary risks. For any resilience measures to be durable and long lasting it would be advantageous if they exhibited intrinsic adaptive capacity. To estimate future environmental trends, it is possible to use climate change forecasts and future planning scenarios.

In terms of climate change, a recent audit of Scottish progress, "How well is Scotland preparing for climate change?" published by the UK adaptation sub-committee (2011) includes specific consideration of utility and transport networks. In overall terms the forecast includes warmer and drier summers, wetter and milder winters, together with a hard-to-quantify increase in frequency and impact of extreme weather events. Features of Scottish geography, society and organisation which have been particularly noted are:
1/ Concentration of population in coastal urban centres
2/ A number of vulnerable crowded transport and communication network corridors between population centres
3/ A human population with a slightly older age profile compared to the rest of the UK.

In terms of future planning scenarios there are Chatham House reports by the Royal Institute of International Affairs (Unsettled times, 3 stony paths to 2015, 1996; Navigating uncharted waters, constructive approaches to complexity, 1997) plus more specific forecast scenarios including infrastructure effects from the Urban Futures research project 2008-2012.

The value of these forecasts is that the range of directions of travel (the design conditions envelope) can be used to list extremes against which future resilience of infrastructure can be tested i.e. it is not necessary to take a view on the most plausible 'direction of travel'; only to test network service levels against reasonable limits in any direction. In other words, if the possible average temperature increase can range from zero to 4 degrees and winter precipitation increase from zero to 10 percent then resilience against heavy snowfall would take the zero degree, 10 percent higher precipitation route. Similarly, if traffic intensities were forecast to increase between minus 20 and plus 50%, say then the most onerous could be used to test resilience in combination with climate change forecasts.

Therefore, it is envisaged that natural and accidental events can be quantified to test resilience by modifying the cabinet office report limits in line with a combination of forecast climate change effects and sociological future planning scenarios.

2.3 The role of asset management

2.3.1 Definition and purpose

The Publicly Available Specification (PAS) 55 definition of asset management is "the systematic and coordinated activities and practices through which an organisation optimally and sustainably manages its assets and asset systems, their associated performance, risks and expenditures over their life cycles for the purpose of achieving its organisational strategic plan."

The European Federation for National Maintenance Societies has a simpler definition, reported in Lloyd (2010), "the optimal lifecycle management of physical assets to sustainably achieve the stated business objectives."

The draft ISO 55000 definition of asset management is (Asset Management – an anatomy) "the co-ordinated activities of an organisation to realise value from assets".

The UK Institute of asset management website states the profession "deals with the optimal management of physical asset systems and their life cycles. It represents a cross-disciplinary collaboration to achieve best net, sustained value for money in the selection, design/acquisition, operations, maintenance and renewal/disposal of physical infrastructure and equipment."

An earlier International Infrastructure Management Manual (IIMM), 2002 edition, definition is "The combination of management, financial, economic, engineering and other practices applied to physical assets with the objective of providing the required level of service in the most cost-effective manner".

Due to the comprehensive supporting details available within PAS 55, and the contemporary work taking place to develop this into an international standard, this author proposes to use the PAS55 definition for the purposes of this research. This is also consistent with the use of the same reference for the cross-industry asset management comparison outlined in section 3.1.

The range of definitions reflects both the 'big picture' character and lack of maturity in this field. None of these definitions is particularly helpful in assisting our understanding of the detailed improvements which good asset management seeks to promote. A better explanation follows from consideration of a list of questions which effective asset management should help organisations to answer (Institute of Asset Management 2011: Asset Management – an anatomy), reproduced below:

• Do you understand the risk profile associated with your asset portfolio and how this will change over time?

• Do you understand the business consequences of reducing your capital investment or maintenance budgets by ten percent over the next five years?

• Can you justify your planned asset expenditures to external stakeholders?

• Can you easily identify which investment projects to defer when there are funding or cash flow constraints?

• Do you have the appropriate asset data and information to support your Asset Management decision-making?

• Do you know if your people have the right competences and capabilities to manage your assets?

• Do you know which Asset Management activities to out-source?

The same source goes on to state that asset management "converts the fundamental aims of the organization into the practical implications for choosing, acquiring (or creating), utilizing and looking after (maintaining) appropriate assets to deliver those aims. And it does so while seeking the best total value approach (the optimal combination of costs, risks, performance and sustainability)."

The broad basis of asset management, combined with the range of origins of technical specialists whose work brings them into contact with the developing discipline, mean that any definition must be wide ranging. The 'meaning' of the discipline is best captured, as above, by listing elements of its purpose.

A recent analysis of the scope and content of asset management is listed in the contents of 'Asset Management – an anatomy' which includes 39 subjects in 6 groups as shown in Table 4. Resilience Analysis is specifically included in group 6, subject 2, where it is described in business continuity terms.

Table 4 Anatomy of Asset Management

SUBJECT GROUP	SUBJECT
Asset Management Strategy and Planning	Asset Management Policy Asset Management Strategy Demand Analysis Strategic Planning Asset Management Plans
Asset Management Decision-Making	Capital Investment Decision-Making Operations & Maintenance Decision-Making Life Cycle Cost and Value Optimisation Resourcing Strategy and Optimisation Shutdowns & Outage Strategy and Optimisation Aging Assets Strategy
Lifecycle Delivery Activities	Technical Standards & Legislation

	Asset Creation & Acquisition Systems Engineering Configuration Management Maintenance Delivery Reliability Engineering and Root cause analysis Asset Operations Resource Management Shutdown/Outage Management Incident Response Asset Rationalisation & Disposal
Asset Knowledge Enablers	Asset Information Strategy Asset Knowledge Standards Asset Information Systems Asset Data & Knowledge
Organisation and People Enablers	Contract & Supplier Management Asset Management Leadership Organisational Structure & Culture Competence & Behaviour
Risk and Review	Criticality, Risk Assessment & Management Contingency Planning & Resilience Analysis Sustainable Development Weather & Climate Change Assets & Systems Performance & Health Monitoring Assets & Systems Change Management Management Review, Audit and Assuranc Accounting Practices Stakeholder Relations

Those same 6 groups are alternatively shown in the conceptual model shown in Figure 7.

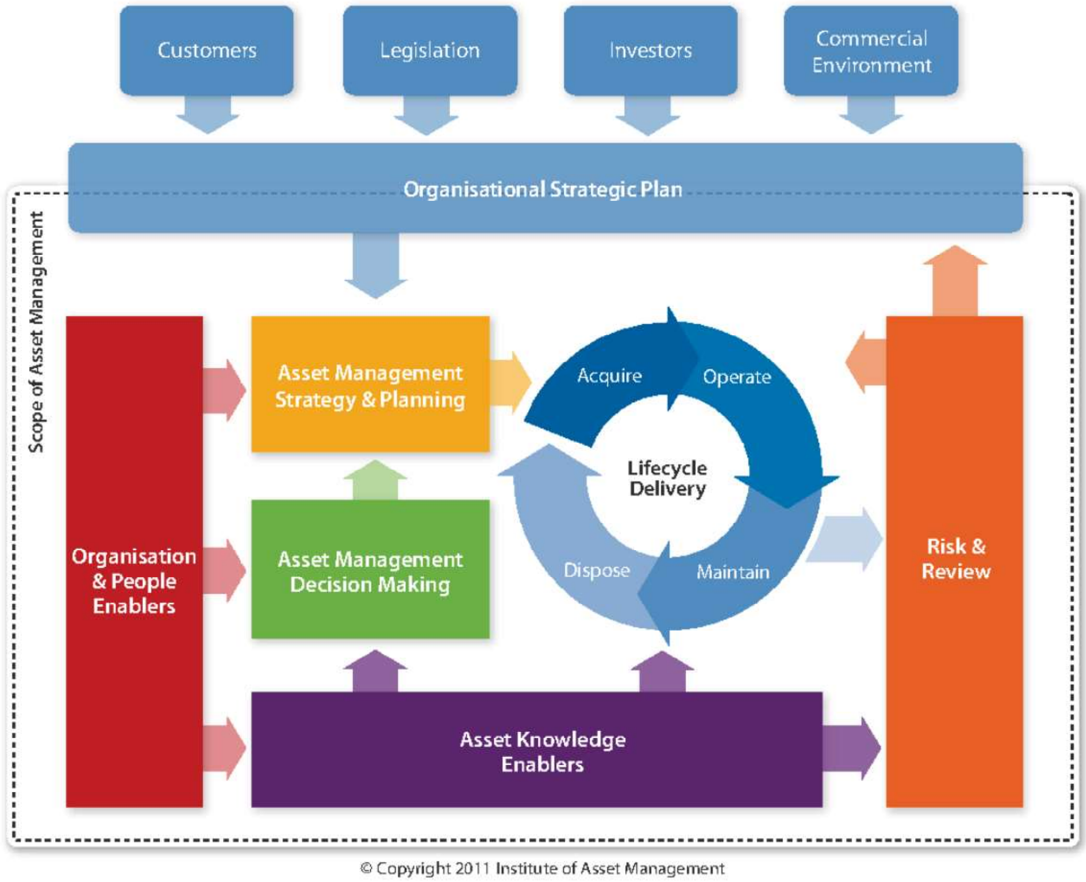


Fig 7 Institute of Asset Management Conceptual Model (from Asset Management - an Anatomy)

2.3.2 Whole life costing and whole life risk analysis

Consideration of a life cycle view and decision making on a whole life cost basis are recognized as critical to effective asset management and "is now accepted by the civil engineering community throughout the world" (Frangopol and Furuta 2000). This accounts for a complete group of life cycle delivery activities and a 'life cycle cost and value optimisation' topic being in the asset management anatomy considered in 2.3.1 Indeed, one of the core principles of asset management is the duty to consider the value/cost of alternatives or intervention strategies on a life cycle basis. This principle also applies to any resilience analysis, vulnerability and threat analysis or any other risk analysis where competing outcomes or actions are compared, in as far as detailed data are available to support decision making. There is some contractor and commissioning client experience of assessing whole life costs arising out of the UK private finance initiative (PFI) programme of capital works.

A multidisciplinary approach to obtaining maximum economic benefit from physical assets over their complete life cycle, or terotechnology, was developed in the UK around 1960 (Boussabaine & Kirkham 2004). It involves systematic application of engineering, financial, and management expertise in the assessment of the lifecycle impact of an acquisition. This was followed by a development of terminology (Boussabaine & Kirkham 2004) to 'cost-in-use', 'life-cycle costing', 'whole life-cycle costing' up to the ISO 15686 terminology below.

Definitions of whole life cost (WLC) and life cycle cost (LCC) are included in ISO 15686, part 5, as below:

WLC is the "methodology for the systematic economic consideration of all whole life costs and benefits over a period of analysis as defined in the agreed scope". It thus includes all relevant costs and benefits (including LCC, non-construction costs, income and externalities) but can be applied to any duration under analysis.

LCC is the "cost of an asset, or its parts throughout its life cycle, while fulfilling the performance requirements". The duration is 'set' but all economic factors are not. These costs are directly attributable to the element in question, over the construction, maintenance, operation, occupancy and end of life periods.

Whole life costing typical stages for infrastructure assets are listed in table 5 below.

It is worth noting that 'life' can mean economic, functional, legal, physical, social or technological life.

The need for a common work breakdown structure as a means of comparing and trading off capital and maintenance works in order to arrive at the lowest WLC determination has been recognised. Marenjak (2004) has proposed a structure for building work.

Table 5 Life cycle phases (Source: CIRIA report C677, 2009, Table 1.2)

Life cycle phase	Example activities in phase
Inception	➢ building the business case for action ➢ demand forecasting ➢ defining requirements ➢ stakeholder involvement.
Feasibility appraisals for whole-life options	➢ evaluating different solutions and associated risks/benefits ➢ selecting of procurement route (such as private finance initiative, framework ➢ contract, design and build, separate design and construction contracts) ➢ producing the project brief.
Plan and design	➢ planning applications ➢ public inquiries ➢ tendering ➢ appointment ➢ outline and detailed designs ➢ whole-life costing ➢ specifying materials ➢ environmental assessment
Construct and handover	➢ construction scheduling ➢ supply chain analysis ➢ waste management and other environmental management ➢ subcontractor management ➢ commissioning ➢ post-commissioning evaluation.
Operate and maintain	➢ service delivery ➢ performance monitoring ➢ planned maintenance ➢ unplanned repairs ➢ condition monitoring ➢ demand forecasting ➢ deterioration modelling ➢ supply chain requirements
Renew or dispose	➢ performance audit ➢ improvement and upgrade ➢ replacement ➢ closure ➢ decommissioning ➢ deconstruction, demolition and recycling ➢ sale ➢ transfer or end of liabilities

A corresponding structure for consideration of infrastructure elements needs to be developed and this could be based on an adapted Civil Engineering Standard Method of Measurement. McNicol (2008) has tackled this and the proposal could be the basis of any framework. Any whole life cost exercise for highway works will take account of proposed depreciation and accounting rules outlined in the CIPFA Code of Practice on Transport

Infrastructure Assets 2010. Some of the advice on discount rates and asset lifespans will be more widely applicable.

The companion need to ensure that staff time spent on analysing elements of assets is cost effective (that the analysis exercise adds more value than it costs) is also important if asset management tools and principles are to be widely used. One way of focussing resources on the most important elements is to use the ‘theory of significance’ used by Marenjak (2004). This demonstrates low percentage errors in overall cost turnouts when costs are optimised only for elements which individually total higher than the average element cost for the project i.e. only the most cost significant elements need be assessed in any comparison or analysis.

There is a considerable body of academic papers and textbooks concerned with bridge and structure maintenance on a whole life basis (Frangopol & Furuta 2000, Ang 2008, Frangopol & Liu 2007). These usually include statistical treatments of risks, loading, environmental factors and load carrying capability.

A whole life costing web based tool has been developed in the University of Dundee; marketed by a spin off company called Whole Life Consultants Ltd, complies with ISO 15686, and is flexible enough to be applied to infrastructure elements. This could be used to undertake whole life cost comparisons and associated sensitivity analyses.

While whole life costing is a major element of asset management, the main objective of stages 1 and 2 of this research is to assess progress in implementation of asset management in the UK. It will therefore also be useful to look at the history behind the world-wide growth of the discipline of asset management.

2.3.3 Development of asset management

The modern discipline of ‘asset management’ of physical (as opposed to financial) assets has developed in the English speaking world but has now spread world-wide with the publication of international standard ISO 55000 in 2014 and the formation of the Global Forum on Maintenance and Asset Management, which is an umbrella group for national associations. Members include the Society for Maintenance and Reliability Professionals in the USA started in 1992 and the UK Institute of Asset Management, founded by utility companies in 2004.

Two examples of the origins of asset management should suffice to explain the drivers behind this discipline. Foster & Monkman (2000) list several factors behind the importance of asset management in New Zealand, leading to the publication of their first asset management manual in 1996. These factors are:

- Large amounts of similar aged infrastructure requiring renewal at the same time.
- Difficult decisions on prioritising expenditure; arising from the above.
- Political recognition and support of the importance of planning for the long term viability and maintenance costs of infrastructure.
- Paying for historical deferred maintenance; i.e. a backlog had built up
- Regulatory issues; local authorities required infrastructure owners to quantify and fund asset depreciation adequately. This included the requirement to compile asset management plans.

Their National Asset Management Steering Group (NAMS) now supplies an International Infrastructure Management Manual 11th edition and is a combined effort of New Zealand and Australian professional bodies.

Al-Hajj and Al-Saadi (2002) describe the origins of asset management in the North Sea oil and gas sector for Shell Group. The twin shocks of a drop in oil price along with increased safety costs arising from the Piper Alpha disaster in the second half of the 1980's demanded a rethink of organisational and operational costs which resulted both in the implementation of ILS techniques together with an ending of 'silo working' in the industry. Their asset reference plans encourage team-working and provide single point accountabilities which allow improved control over expenditures. Overall benefits are claimed "The asset management process enables one to maximise the value of an asset by making use of resources, i.e. staff, money and technology, over the life cycle of the asset. It will certainly enhance efficiency, integrity, productivity, reserves replenishment and ultimate recovery (growth) of a company and therefore profit"

The CIRIA C677 report (2009) gives a range of examples of the application of asset management across utility and infrastructure sectors in the UK. Case study examples of rail, marine, roads and water applications give a flavour of recent use.

A view of the dissemination of asset management practice in the UK is described in section 4.1.

2.3.4 Application to resilience and future threats

Along with a life cycle view, the analysis tools suggested within asset management guides are the technical 'engine' behind value improvements arising out of adoption of an asset management philosophy. ILS techniques are one set of these tools and are specifically included in sections 5.2.2 (Operations and maintenance decision-making) and 5.3.6 (Reliability engineering & root cause analysis) of 'Asset Management – an Anatomy'. Their potential value in failure analysis and related decision making is therefore acknowledged by asset management practitioners.

One of the major changes in emphasis between 'Asset Management – an Anatomy' and the earlier PAS55 is the inclusion of an element of looking to the future as well as identifying future 'shocks' from a business continuity viewpoint. Thus sections 5.1.3 (Demand analysis), 5.6.4 (Weather & climate change) and 5.6.2 (Contingency planning & resilience analysis) are given increased emphasis. The current summary of the state of understanding of the remit of asset management in the UK therefore specifically entreats practitioners to address the resilience of their operations in the face of future business threats. Reference is made to BS 25999 Business Continuity Management. The application of ILS techniques to threat and vulnerability studies, as part of the BS 25999 business continuity framework is where ILS can contribute to resilience improvements.

Woodhouse (2001) assesses a range of tools against a 5 part 'total business impact' score of measurable success including; reliability/risk management, efficiency, longevity, compliance and 'shine' factors. The tools are Total Quality Management and Six-Sigma, Reliability-centred Maintenance, Total Productive Maintenance, Risk Based Inspection, and Root Cause Analysis. He makes the case for using a combination of these tools under an overall asset management programme. It is vital, therefore, to use the strengths of FMECA and RCM in resilience analysis, while being aware of the availability of other tools. It is also vital that enough detailed historical failure data is available and in this respect the importance of asset management in promoting collection and organisational improvements should be clear.

2.4 The role of integrated logistics support

2.4.1 History and application to civil engineering infrastructure

Integrated logistic support (ILS) can be defined as: a structured management approach aimed at ensuring that assets are designed and maintained to deliver maximum whole life value whilst achieving the required levels of performance and reliability (based upon Blanchard & Fabrycky 1991). Availability, reliability, durability, maintainability, supportability and safety are all considered in as much detail as possible, normally by an expert panel. ILS comprises a suite of tools including failure modes, effects and criticality analysis (FMECA); reliability centred maintenance (RCM); Availability, reliability and maintainability analysis (ARM); level of repair analysis (LORA); fault tree analysis (FTA); logistic support analysis (LSA). These are defined in the glossary.

The application of ILS techniques has developed from US military requirements, through development in the US aeronautical industry, to more widespread adoption by oil and gas companies, followed by worldwide utilities. These techniques can be seen as a tool chest and have proven their effectiveness in practical applications. Definitions, rules and guidance are included in U.S. military standards, e.g. MIL.STD-1388 (US Department of Defense 1983). They have traditionally been applied to electrical and mechanical systems as these systems have a/ regular failures of small components which can disrupt functionality, b/ regular time consuming maintenance needs, c/ shown failure patterns and predictable design lives through study of comprehensive failure data. This research aims to discover whether this organisational focus on reduced maintenance costs can be replicated when applied to resilience of civil engineering infrastructure. A demonstration of the applicability of FMECA and RCM (the other tools generally require more data than has been available for civil engineering and building elements) to building elements (El-Haram & Horner 2002) has demonstrated the potential for significant overall cost savings. Marenjak (2004) has also applied these techniques to whole life costing of building structures and repeated the demonstration of savings, albeit the effectiveness of application is hindered by lack of systematic recording of failure data.

ILS techniques therefore depend on the availability of relevant data regarding life duration, maintenance regimes, condition surveys and these are all more likely to exist in an organised form when an asset management strategy is in place.

FMEA is essentially a structured method of assessing failure modes and their effects, using a group of experts who have access to historic failure data. An RCM exercise takes the results of the FMEA analysis and establishes optimum maintenance practices to minimise overall costs.

The purposes of an FMECA are (Jones 2006):

a) Hazard elimination
b) To identify where the loss of function results in the loss of whole system functionality
c) To provide a clear method for determining when a loss of function has occurred and to aid in diagnosing which item has to be repaired
d) To provide a basis for support planning (i.e. to resurrect the system in case of failure)

The objectives of an RCM exercise are (Anderson & Neri 1990)

1/ to make certain that equipment achieves the defined reliability level

2/ to reduce unscheduled maintenance and eliminate ineffective preventive maintenance

3/ to focus maintenance consideration on a system that may affect safety, environment, economics or operation

4/ to increase system availability

Documented records of the application of ILS techniques to civil engineering infrastructure are patchy. The impression is given that FMEA has been applied on limited examples (Atkins and Arup 2011 reports for the rail industry). Penetration has been deepest in the energy supply sector (oil, gas, nuclear) and regulated sectors (energy and water distribution plus telecommunications). The rail industry use of ILS is described in papers by Marquez et al (2007), Quigley et al (2006) and Reynolds (1998). Two International Atomic Energy Agency papers (Hezoucky 2007 and IAEA 2008) cover the nuclear generation industry and Komari (2009) covers information technology. Water company applications are often mentioned in their annual reports to the regulator.

2.4.2 Barriers to successful transference

In order to demonstrate the cost effectiveness of transferring ILS techniques to civil engineering infrastructure it will be necessary to compare resources expended (input – mostly staff time) against economic advantages arising from the exercise (resulting from maintenance practice changes and increased resilience to threats). This requires a whole life cost comparison which depends upon the use of a common costing framework for construction and operational activities.

Data sufficiency is a major potential impediment. Historically, people responsible for civil engineering construction and maintenance have not been focused on accurately recording failure data. It may be that the successful application of ILS techniques will provide an incentive for better record keeping in future.

There is a general perception that the range of environmental and loading factors which combine to cause civil engineering failures are so variable and site specific that an exercise in fault identification may not be transferable to similar sites and future applications. In other words, the staff time expended in an ILS assessment may not yield overall benefits. The theory of significance (see the glossary) may obviate this by allowing concentration on the most important elements only.

It is accepted that mechanical and electrical systems include components which will fail and require replacement at approximately predictable intervals. The increased wear due to motion or electrical use makes this inevitable or at least cost effective. Many civil infrastructure elements or structures, however, have larger factors of safety against failure because either the consequences of failure or service interruption are large or the scale of resources required to replace failed elements is large. Often these two factors are combined. Some infrastructure elements are effectively designed for an infinite life e.g. some major trunk roads, providing regular maintenance is undertaken (carriageway surfacing). In essence, an over-design is necessary to cope with ill-defined environmental and loading conditions and this over-design minimises the subsequent maintenance needs. The perception is that this reduces the scope for offsetting construction and maintenance costs which may arise from an ILS exercise.

These characteristics of civil engineering elements make local knowledge of circumstances more useful than an accurate quantifiable analysis of, say, mean time to failure for any element. For example, two identical diesel engines in two different enclosures/buildings may be expected to have similar lives; the same may not be true of two identical bridges in different rivers or different climatic zones. This leads many civil engineers to prioritise judgement over calculation whereas this priority is likely to be reversed for mechanical and electrical engineers.

This ‘long life’ characteristic also means that the lifespan of civil engineering elements may be determined by obsolescence in economic, social or functional ways as alternatives to physical failure. This will also need to be taken into account in any ILS analysis.

Marenjak (2004) identifies defining characteristics of the aerospace and construction industries as;

- Traditional construction industry normally allots design and production into separate, defined responsibilities but in the aerospace industry design and production are highly integrated through the use of IT systems
- In the construction industry, traditionally, tendering is normally decided on price instead of value, whereas in the aerospace industry the opposite is true.

- In the construction industry, traditionally, suppliers are rarely consulted early in the design phase, whereas in the aerospace industry suppliers are involved from concept design to assembly.
- Traditional construction industry practice does not always fully consider whole life costs during design, whereas in the aerospace industry performance, whole life cost and ILS are very important

These differences are being blurred to some extent both by enlightened construction clients plus the increasing use of electrical and IT systems in conjunction with civil infrastructure. The increasing interdependencies arising are more suited to an ILS analysis, particularly one focusing on resilience.

2.4.3 Application to ensure resilience

FMEA and FMECA are risk assessment tools. Their purpose is to allow systematic investigation into failure modes and consequences. While this is usually followed by an RCM exercise to determine cost effective maintenance needs in order to guard against failure, the technique is equally pertinent to a study of the resilience of a system. If protection and recovery are both included within the definition of resilience the ILS analysis needs to extend to include the recovery element. If recovery only is being considered this is also applicable.
'Asset Management – an Anatomy' suggests a threat and vulnerability study be undertaken as the main analytical stage of a resilience analysis. The ILS suite seems suited to such an exercise.

This suite of tools allows a disciplined 'bottom up' way of using a risk analysis approach to a/ assess system vulnerabilities and resilience both within a sector and also to b/ compare and prioritise vulnerabilities of cross sector interdependencies in terms of their effect on overall systems resilience. Results can either be used directly within a local area or, longer term, used as input to network models in order to establish resilience indices or similar.

2.5 Summary

2.5.1 Problem statement

Such is the complexity of modern physical infrastructure, and their interdependencies, that expert input to vulnerability and threat analyses is required in order to identify systemic resilience inadequacies. ILS techniques can empower these analyses but depend on the availability of relevant data regarding life duration, maintenance regimes, condition surveys and these are all more likely to exist in an organised form when an asset management strategy is in place.

This literature review has shown the current state of progress in the application of resilience, ILS and asset management upon the management of physical civil engineering infrastructure. The hypothesis of this research is that ILS techniques can be used to marshal expert input – i.e. that ILS can provide the essential 'bottom up' input to best utilise a modelling methodology in order to enhance resilience in a cost effective manner, within the bounds of corporate asset management planning. Section 4.1 shows progress in comparing asset management plans (AMPs). This has acted as a 'way in' to company AMPs which illustrates progress in useful areas such as data collection and existing use of ILS.

A promising use of ILS may be in formalising the risk analysis of system interdependencies and vulnerabilities. A successful case study exercise has the potential to highlight gaps in resilience which can then be prioritised in order of whole life cost benefits.

2.5.2 Boundaries and assumptions

- Technological improvements as opposed to organizational and communication improvements will be prioritized. ILS is best suited to this and recommendations arising are more likely to be useful at a pan-organization level.

- Both protection and recovery aspects of resilience will be considered but more emphasis will be directed towards recovery as major incidents will require this focus.
- Security threats (e.g. from terrorism) requiring specialized or confidential knowledge will not be specifically considered.
- The exercise depends on enough detailed data on costing and business consequences of alternative solutions being made available from participating utilities in order to make an ILS exercise worthwhile.

2.5.3 Parallel research

The current importance of infrastructure resilience is being addressed by a number of wide ranging UK research centres and programmes, generally in a 'top down' manner. These include: Salvo project, Salford University Centre for Disaster Resilience, International Institute for infrastructure renewal and reconstruction (IIRR). University of Leeds Institute for Resilient Infrastructure, Cranfield University Resilience Centre, Living with Environmental Change, Stockholm Resilience Centre, University of Glamorgan Disasters and Resilience Centre, Loughborough University Centre for Organisational Resilience, UK Infrastructure Transitions Research Consortium, Macro project.

This University of Dundee research project will, in contrast, be 'bottom up' and will aim to establish the value of ILS techniques in assessing the resilience of physical infrastructure.

2.6 Stage 1

The UK government has identified nine national infrastructure sectors which require protection against hazards or attack: water, energy, transport, communications, health, emergency services, finance, food and government (National Risk register of Civil Emergencies 2010 edition). The UK Infrastructure Group (2010) counts 5 civil engineering infrastructure sectors – the first four above; and waste. Searching for evidence of asset management planning in the waste sector was unsuccessful and, while disruption to this industry would have national consequences, it differs from the other 4 sectors in as much as the few fixed assets (tip sites and mechanical plant) are not usually regarded in system or network terms. Civil engineering infrastructure assets are less of a business priority in this sector. Also in terms of the criticality of resilience concerns, waste is probably the least important as there should be a period of grace before it becomes a problem. (Keeping the country running 2011). The waste sector has therefore not been considered further.

Asset management principles and techniques are now spread globally through the auspices of the Global Forum on Maintenance and Asset Management. Notable organisations contributing to this include the New Zealand Asset Management Steering Group (formed in 1995 and the organisation behind the International Infrastructure Management Manual), the UK Institute of Asset Management (formed in the early 1990s and the organisation behind PAS55) and the US Federal Administration Office of Asset Management.

A literature search of publicly available asset management publications relating to the 4 remaining UK sectors uncovered some difficulties. Whereas asset management is seen to be of primary importance for infrastructure owners in Australia and New Zealand, the relative youthfulness of the concept in the UK means that organisations describe their asset management benefits and progress as part of publications whose primary purpose is something else. The best example of this is the English and Welsh water companies who include much asset management information in their 5 yearly business plans. Highways authorities (councils) similarly often include their highway asset management arrangements within a management plan which includes other departments and properties too. Energy distribution companies usually produce maintenance plans rather than full asset management plans. While direct access to water, transport and energy supply asset management planning information was confused by nomenclature, direct access to other energy and communications infrastructure sector plans suffered through lack of publicly available information. The shortage of primary sources meant that secondary sources had to be relied on, which included textbooks, conference presentations, academic papers, interviews and articles included on the Institute of Asset Management (IAM) website.

Assistance from a French transfer student for 3 months has contributed to this research effort by comparing stage 1 asset management implementation across the energy supply utility sector.

Both IAM textbooks (Deadman and Lloyd) give authoritative overviews of asset management implementation. Both include appraisals of the most appropriate applications of ILS and RCM tools, in comparison with rival techniques. Deadman introduces an 'Asset Management Capability Model' which shows how the best fit model for any company varies with business climate, sector complexity, regulatory goals, analytical tools required, company organisation and size, and team make up. This analysis of the factors affecting the shape of AM implementation is beyond the scope of this 'snapshot' of progress across the 4 main infrastructure sectors, however, but is very useful background where publicly available primary material is hard to uncover.

2.7 Stage 2

Asset Management Plans (AMPs) from the following organisations have been reviewed:

Anglian Water, Yorkshire Water, Herts County Council, South Yorks Transport Partnership, Highland Council Roads, Transport Scotland, Glasgow City Council, Highways Agency, Scottish Water Delivery Plan, Stirling Council Roads, Newcastle City Council Highways, Bournemouth Highways.

Dundee Transport Strategy and Moray Transport Strategy have also been reviewed.

Detailed report sheets have been produced, comparing AMP progress against the requirements of PAS55, for the following organisations and these are included in appendix A2:

Scottish Water, Anglian Water, Hertfordshire County Council Highways, South Yorkshire Highways, Transport Scotland.

From the above records, general comparisons and observations can be made and these are listed in section 4.2.

2.8 Stage 3

2.8.1 Resilience and reliability

The contemporary importance of resilience to civil engineering infrastructure is related to (Rinaldi et al, 2001):

- increasing interconnectedness between different systems (e.g. information technology and power supply networks supporting infrastructure) and the less obvious vulnerabilities which result.
- Lengthened supply chains combined with budgetary pressures which can result in reduced capability headroom in the event of unforeseen circumstances.
- Increased risks and uncertainties due to both human agency and environmental hazards.
- Reduced public acceptance of failures, with consequential reductions in public standing of the relevant organisation and industry.

Resilience can be understood as having 4 aspects; resistance, reliability, response and recovery, redundancy, (Cabinet Office, March 2011). Design or operational improvements can address any of these four elements. A fuller definition, adopted for use in this report, is: 'Given the occurrence of a particular disruptive event (or set of events), the resilience of a system to that event (or events) is the ability to reduce efficiently both the magnitude and duration of the deviation from targeted system service levels' (adapted from Vugrin et al, September 2011).

If it is wished to increase resilience then either resistance must be increased or, more usually, the "magnitude and duration of the deviation from targeted system service levels" must be reduced (Vugrin et al, 2011) In other words, recovery effort must be minimised.

One method of doing this is to introduce redundancy to the system. Another method is the use of 'firebreaks' to prevent large scale catastrophic collapse. "Service levels" in this instance have been equated to 'availability to users' in the system level FMECA exercise.

FMECA methodology in particular, is designed to assess and prioritise the effect of failure causes on a system. It is a short step to use it as a central part of a resilience analysis.

2.8.2 Case study description

Designed by William Fairhurst and built by William Logan, the Tay Road Bridge construction was begun in March 1963 and was completed by August 1966. The River Tay is a tidal firth at this location with a width of 7365 feet, a maximum water depth of 60 feet and a maximum tidal race of 6 knots. The bridge takes vehicles, services and pedestrians between Dundee and Fife. The Fife end (South) connects to a rural dual carriageway; the Dundee end to the city centre.

The bridge consists of 42 spans of various lengths, although many are 180 feet. Each span consists of twin steel box girders with a concrete deck, supported on twin concrete columns. Total concrete weight is 140,000 tons, reinforcing bars 4,600 tons and structural steel 8,150 tons. Otherwise independent girders are linked with cross beams and the dual carriageway decks support a central precast concrete pedestrian walkway. The bridge supports one ten foot wide pedestrian/cyclist lane and two 22 foot wide dual carriageways.

There is a continuous gradient rising from Dundee to Fife and the 4 navigation spans are towards the Fife end. Three piers at the two main navigation channels have recently been protected against ship collision damage by the construction of separate concrete bulwarks.

Approximately 9.2 million vehicles are carried annually and there is a navigation requirement to allow ships to transit to and from Perth harbour. The nearest alternative Tay crossing is 25 miles distant; Friarton bridge at Perth. Therefore, a maximum 50 mile diversion would be necessary if the bridge ceased to function.

Operation and maintenance is the responsibility of the bridge manager and his 35 staff. Engineering control is vested in the chief engineer of Dundee District Council. Bridge affairs are managed by a board of councillors taken from the local councils of Dundee, Fife and Angus. Until February 2008 they were funded through traffic tolls but are now funded directly by the Scottish Government. Management arrangements are therefore separate from Transport Scotland's trunk road management duties. This allows a tailoring of nationally recommended inspection and maintenance regimes to the specific needs of the bridge.

Main replacement/augmentation works undertaken during the life of the bridge have been: Toll booth removal, all main bearings replaced, running surface heating cables installed near toll booths, viewing platforms removed, self-propelled maintenance gantries installed, North bank ramps realigned, collision protection to main navigation piers constructed, water main and throughput services cables removed, spalling concrete on columns repaired and cathodic protection system installed.

Most of this information is taken from Scottish Screen Archives, 1967; Borthwick 1966; Tay Road Bridge website.

2.8.3 Collection of records

Documents and data have generally been supplied or verified by the bridge manager. The main sources are listed below.

1/ Drawing TAY-REF-100-01: used to construct a unit based model of the physical structure.

2/ Drawing TAY-REF-006-01: used to construct a unit based model of the physical structure.

3/ Replies to Question list 26/04/12: used to verify the physical model and as background knowledge for the FMECA.

4/ Notes of meeting with bridge manager 25/04/12 and ICE bridge site visit 24/05/12: as for 3 above

5/ Note of meetings with bridge manager 22/03/13 and 05-04-13: to verify both FMECAs and to give feedback on the RCM exercise.

6/ Component function list and general data sheet gleaned from website, text book and film of bridge construction; Appendix B1: used to construct a unit based model of the physical structure.

7/ Bridge management reports and records; the Tay Bridge website: used for the system FMECA exercise.

8/ Operational restrictions between January 1999 and February 2013 inclusive: used for the probability, severity and detectability ratings for the system level FMECA.

9/ Email responses to questions, of 29-01-13: used to inform the unit level FMECA and RCM exercises.

10/ A list of major capital works expenditure to repair, replace and maintain parts of the bridge: used in section 2.8.5 to compare maintenance costs.

2.8.4 Availability records

Item 8 in section 2.8.3 includes all recorded periods of restriction or closure of the bridge to the nearest minute. These are reported at the 3 monthly Board meetings and summaries are made publicly available on the bridge website.

These data have been analysed (Paraskevopoulos, 2013) and split down according to cause, duration and time of day or night. The principal causes of closures pictured in terms of closure durations are shown in Figure 8.

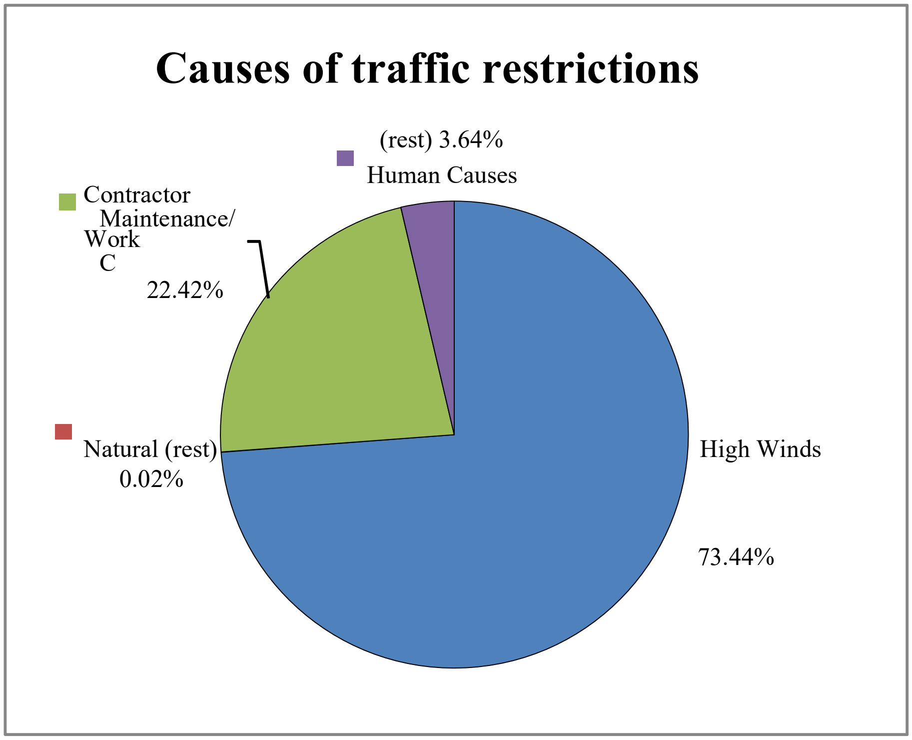


Figure 8 Causes of traffic restrictions

The majority of the wind restriction periods have been in winter. The maintenance closure percentages have been raised due to one-off activities on the North ramps in 2010 and 2011; but for this, the 22% would have been significantly reduced. Therefore, the principal cause of traffic restrictions, measured by time period, is due to high winds.

By relating these to representative daily traffic flow numbers, an assessment of diversionary journey numbers and durations has been made in order to estimate the overall social costs of bridge closures and restrictions. These social costs are based on Transport Scotland Value of Time guidance with a base year of 1999. The findings are summarised in Table 6.

Table 6 Total cost of traffic restrictions

Total cost of traffic restrictions 1999-2012	£28,247,506
Portion due to maintenance	£16,016,409
Portion due to high winds	£10,858,280
Others	£1,372,817

Most of the restricted periods due to high winds impact on only a portion of vehicles, according to the wind speed trigger points below.

Operational protocols for the bridge, in terms of wind speed, are listed below.

Table 7 Wind speed thresholds

Wind Speed Threshold	**Traffic Modifications**
45 miles per hour	No Double-Decker Buses
60 miles per hour	No High-Sided Vehicles, Pedestrians, Cyclists
70 miles per hour	Only cars allowed
80 miles per hour	Total Closure

This accounts for the wind costs being less than social costs due to maintenance, because maintenance closures usually affect all traffic. The maintenance costs are also increased due to unrepresentative years in 2010 and 2011, when major alterations were carried out to the North abutment spans.

An annual summary of restricted periods due to high wind speed is shown below.

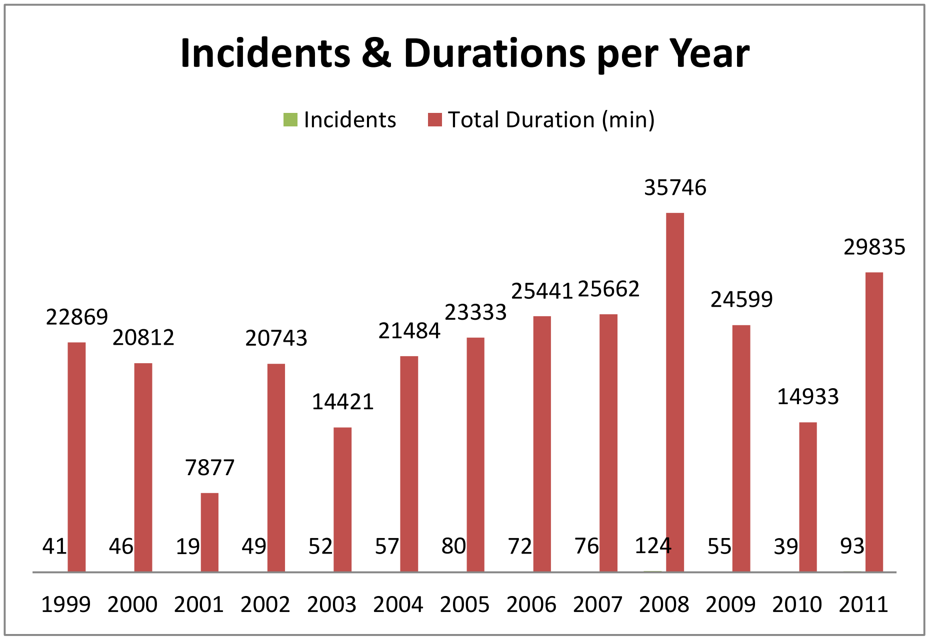


Figure 9 Wind speed restrictions

In round terms there are 20 full days per year where traffic restrictions due to high winds are in place. As this is the major cause of traffic restrictions on the bridge, a search was undertaken to establish whether this problem had been tackled for other long bridges. The value of wind deflectors has been recognised for other long bridges such as the existing Severn bridge and the new Queensferry crossing so the effectiveness of these in improving the availability of the bridge to users has been recognised elsewhere. The Tay bridge stoppage data were therefore used to undertake a cost benefit exercise to assess the value of retrospective installation of wind shielding and the results are shown in section 4.3.4.

There are a number of qualifications to the employment of the data to this exercise, of which three of the most important are listed below:

1/ Double decker buses have been assumed to divert via Perth rather than be replaced by single deckers. This may over-estimate the resultant costs.

2/ The financial model has taken no account of additional congestion in Dundee due to bridge restrictions. This may under-estimate the resultant costs.

3/ A structural check on the ability of the bridge to carry the additional loading from the windshields has not been undertaken, therefore the feasibility has not been established.

2.8.5 Records of expenditure on maintenance projects

A list of significant expenditure on repair, replacement or enhancement projects since bridge construction in 1966 has been supplied or verified by the bridge manager. These have then been aggregated into categories, adjusted for construction inflation and shown at common 1966 rates in order to display relative costs at a common scale. A summary breakdown is shown in Table 8 below. There is no record, or awareness, of major expenditure on bridge maintenance prior to 1982 so all the costs have been incurred in the past 31 years.

This summary allows the main maintenance requirements over the period 1982 to 2012 to be highlighted. 71% of the initial construction cost has been expended on major maintenance works up to year 46 of a 120 year design life. This excludes ramp realignment at the North bank, where the need for the works was prompted by the Dundee Waterfront development (and funded separately from the bridge board). The ‘strengthening work’ includes both works to cope with heavier lorries plus the collision protection works at the navigation span piers.

Table 8 Maintenance expenditure summary

Expenditure on Maintenance Projects	Spend on 1966 equivalent base year (thousands)	Percent of maintenance spend
Parapet replacement	21.78	0.64
Concrete repair	681.79	19.99
Steel painting	342.24	10.04
River surveys	2.15	0.06
Maintenance access	251.09	7.36
Joints	233.75	6.86
Accommodation	14.84	0.44
Surfacing enhancements	32.91	0.97
Visitor improvements	23.33	0.68
Control improvements	155.74	4.57
Bearings	816.30	23.94
Strengthening works	834.02	24.46
Sub total	3409.93	100.00
(Initial Construction)	4800	
Total	8209.93	

The value of this table is that it focusses management attention on the major lifecycle maintenance costs. Although not carried out under this project, both detailed FMECA and focussed RCM assessments could therefore be targeted at the major cost items in greater depth.

3 Methodology

3.1 Stages 1 and 2

In order to compare asset management planning across sectors at stage 1 a common assessment benchmark is required. Four templates were considered following a search of authoritative industry guidance. The International Infrastructure Management Manual (IIMM) was considered but the structure didn't readily lend itself to a 'tick sheet' list of headings to compare company progress. Difficulties acquiring an up to date copy also raised doubts about it being sufficiently up to date.

There is a web based asset management maturity checklist from the Institute of Asset Management (theiam.org) but this is more useful as an audit tool where access is available to all company tools, techniques, case studies and staff interviews. For our purposes it is a little too detailed. A spreadsheet based list of headings (see appendix A1.2, from Lloyd (2010), based on Network rail regulation headings) was then trialled against a list of subject headings in Publicly Available Specification(PAS) 55. Reproducibility was checked by having 2 different researchers use them on the same reports and the checklist of PAS55 headings was found most manageable and had the most rigorous back up details (from the PAS55 text) to provide explanations to ensure consistency in application. These checklists were applied to asset management planning documents at stage 2 (see Appendix A2) and are listed in Table 9 below.

Table 9 PAS 55 Asset Management Comparison Template

4.1 (reference numbers from PAS 55)	General requirements: Define and document the scope of the system; Control of outsourcing
4.2	Asset management policy

4.3.1	Asset management strategy
4.3.2	Asset management objectives
4.3.3	Asset management plans
4.3.4	Contingency planning
4.4.1	Structure, authority and responsibilities
4.4.2	Outsourcing of asset management activities
4.4.3	Training, awareness and competence
4.4.4	Communication, participation and consultation
4.4.5	Asset management system documentation
4.4.6	Information management
4.4.7.1	Risk management processes
4.4.7.2	Risk management methodology
4.4.7.3	Risk identification and assessment
4.4.7.4	Use and maintenance of asset risk management
4.4.8	Legal and other requirements
4.4.9	Management of change

4.5.1	Life-cycle activities
4.5.2	Tools, facilities and equipment
4.6.1	Performance and condition monitoring
4.6.2	Investigation of asset-related failures, incidents and non-conformities
4.6.3	Evaluation of compliance (with legal and regulatory requirements)
4.6.4	Audit
4.6.5.1	Corrective and preventative action
4.6.5.2	Continual improvement
4.6.6	Records
4.7	Management review

3.2 Stage 3

3.2.1 Introduction

The primary aim of this assessment of the Tay Road Bridge operating and technical management arrangements is to apply Integrated Logistics Support (ILS) analytical tools with a view to assessing the extent to which they are helpful in identifying vulnerabilities, maintaining reliability and enhancing resilience.

The Tay Road Bridge had the following advantages as a civil engineering asset for an ILS case study:

1/ The structure is a repetitive simple span structure. It is local and high profile, with easily defined physical and operational boundaries. The governing board was solely focussed on the bridge.

2/ Bridge staff were open to sharing technical details, historic availability and maintenance spend records. They were willing to apply the necessary 'real life' checks on the results.

3/ Cost penalties for restricted availability were easily calculated in that traffic numbers and diversion routes were easily defined.

4/ Bridge staff were in the process of applying asset management thinking to their asset so the results of the exercise could be of operational benefit.

Industry standard assessment methodology and associated forms have been tailored as necessary in order to highlight resilience and reliability as opposed to their normal function of risk control and minimising whole life costs.

Two tools are applied; Failure Modes, Effects and Criticality Analysis (FMECA) and Reliability Centred Maintenance (RCM). This arose out of earlier research (Marenjak 2004) which identified these two as most likely to provide benefits when applied to physical infrastructure. Other ILS tools listed in 2.4.1 have potential value in specific circumstances but are less widely applicable.

Failure Modes, Effects and Criticality Analysis (FMECA) was applied at two levels: a unit level and a system level. In addition to allowing comparison of the two sets of results, this dual approach allows consideration of the asset both as a conveyance system for users, and a physical or structural model to carry loads. Possible failure causes are also split into two: those affecting only reliability (i.e. those which the design might reasonably have been expected to include consideration for) and those arising from unforeseen and less probable causes which are generally outwith normal design considerations. Both affect resilience. Both can cause functional failure. Widening the boundaries to include less frequent failure causes is particularly appropriate in long life, high cost investments such as civil engineering assets. That is, the failure costs to society are of such impact that consideration of less frequent failure causes is worthwhile. It is considered that consideration of a more detailed, say part, level (see “Infrastructure Spatial Scale for Analysis” in the glossary) will only be necessary if failure causes or modes depend on analysis at that level. An outline cost-benefit analysis of a physical improvement to aid resilience of the bridge is included to demonstrate that real improvements can arise from the application of ILS tools.

The second tool, Reliability Centred Maintenance (RCM) is deployed on failure modes at a unit level. This results in recommended maintenance responses. Financial or operational improvements arising therefrom will always be application specific and can only be evaluated over time. There is the opportunity for results from these two exercises to be incorporated into the bridge asset management plan as that develops into a detailed document. The findings of the RCM exercise can feed into bridge staff efforts to increase or maintain bridge condition indicator scores.

3.2.2 Case study boundaries

3.2.2.1 Physical boundaries

The bridge system has been considered in this assessment as including a number of subsystems; bounded as below.

1) Physical structure: the southern limit is the white lining where bridge lanes meet the roundabout perimeter. The northern limit is the equivalent where the ramps meet traffic originating from or destined for different routes. Included within this are the bridge offices and the sea bed down to underside of foundation level. Foundations for all load bearing units are included insofar as they are necessary for the support of these units.

2) Electrical: All electrical systems owned and operated by bridge operational and maintenance staff, up to and including the back-up generator and the meter for the electricity supplier.

3) Mechanical: Includes deck inspection gantry and pedestrian lifts. Excludes vehicles and marine craft.

4) Instrumentation, control and automation: all these systems on the bridge, plus the control room.

5)/ Operational support: all guidance and administrative systems to support human control of bridge operations. Travel to work routes have been excluded.

This study is principally concerned with the physical structure between the perimeter of the roundabout at the South end and where bridge traffic leaves or joins other traffic at the North end. The immediate physical environment is considered only where it affects the above five systems by way of failure causes.

While the capability of the ILS tools is such that they could be applied at a more detailed level to test the resilience of the supporting systems, this study concentrates on the operation and maintenance at the level of the system, subsystems and units. Parts could be investigated if needed in order to understand and diagnose failure modes and causes.

Consideration of catastrophic collapse of the entire roads infrastructure is not part of this exercise. For example, neither the consequent congestion impact of a bridge closure, nor the effect on bridge traffic of a major road closure outside the bridge boundaries, is considered. This would have required use of the Dundee council traffic management model.

3.2.2.2 Limits on failure causes

Section 2.2.2, covering the classification of failure causes, which commonly affect infrastructure systems, identified 4 types: terrorism, cyber-crime, natural events and events with human causes. This use of integrated logistics support is not going to consider terrorism (involves national security concerns) or cyber-crime (would require technical skills beyond the scope of this writer). It may be that ILS tools are capable of also addressing these types of failure causes provided that expertise exists amongst the practitioners. Natural events have been renamed 'environment' in the system level FMECA exercise and human causes have been subdivided into human, maintenance shortfall and socio-economic failure categories (refer Appendix B4).

Failure causes which would decimate infrastructure in large areas outwith the bridge environs e.g. meteor strike or nuclear explosion have specifically not been considered on the grounds that, if these events occurred, bridge reinstatement would not be top of the priority list.

Failure causes which are within the control of other management bodies have also been excluded on the advice of the bridge management team; e.g. a drifting ship smashing into a column, while under the control of the Harbour Authority. The FMECA exercise could be expanded in future to include similar failure causes if desired.

Many failure causes have a range of effects over a wide scale. For brevity, a 'most likely' scale and impact have been applied.

3.2.3 Application of ILS tools

Two ILS tools have been applied; failure modes, effects and criticality analysis (FMECA) and reliability centred maintenance (RCM). The application of these tools to a civil engineering asset such as the Tay Road Bridge has required some careful consideration of term definitions, boundaries, functions and feasible failure causes.

The step by step process is described in Appendix B5.3 and applied to the bridge as listed below:

FMECA: This has been tackled at two levels; a system level and a unit level. For each level the process is the same.

(i) Construct a physical model of the bridge. (Appendix B2)

(ii) Construct a functional model of the bridge. (Appendix B3)

(iii) Cross map the physical and functional models so that the impact of failure of a component on performance can be identified.

(iv) Compile failure modes which prevent bridge functions.

(v) Conduct a STEEPLE analysis, covering social, technical, economic, environmental, political, legal and ethical factors, to define a list of causes of failure modes. Edit out very unlikely and mega scale causes. Protecting against highly improbable causes is unlikely to be considered cost effective by public opinion and if geographically wide scale or exceptionally severe causes occur, protection or restoration of a single bridge is not likely to be the highest priority. Categorise failure causes into resilience and reliability groups.

i) Match failure causes to failure modes.

ii) Undertake the FMECA exercise, line by line for each failure cause. Identify causes, effects, probability of occurrence and criticality of failure modes. Prioritise failure modes by allocating a risk priority number.

iii) For the highest ranking failure modes, compare whole life financial costs and benefits of retrospective design improvements to prevent these.

RCM: Maintenance regimes are designed to maintain the function and appearance of particular bridge units. The RCM assessment has therefore been undertaken at the unit level where failure modes can be linked to specific bridge units. An attempt was made to develop an RCM assessment based on the system level FMECA but this proved impractical as many of the failure modes were not directly related to any single unit therefore maintenance regimes could not be focussed and analysed.

The RCM exercise aims to choose the most appropriate maintenance regime type so considers failure modes and consequences rather than causes. The classical steps are listed in Appendix B8.7 and are applied to the bridge as below.

i) List failure modes from the unit level FMECA exercise. Define failure condition carefully in each case.

ii) Define logic diagram for selection of failure consequences. Allocate consequences to each mode.

iii) Define logic diagram for selection of type of maintenance regime. Allocate regime to each mode.

Compare decision with current maintenance practices to identify any benefits of altering the regime.

3.2.4 FMECA methodology

3.2.4.1 The Tay Bridge Physical Model

The bridge structure has been split into substructure-foundations; superstructure-columns and abutments; superstructure-deck; fittings; and services. 37 physical elements are listed under these 5 headings and the one model applies to both FMECA exercises. Relating back to the systems listed in section 2.8.1, the physical structure is the main focus of attention.

The full model is in Appendix B2 and the model elements (termed as units in the spatial scale listed in the glossary) are listed below. Those units in brackets are only considered at the RCM stage, where additional detail was deemed useful.

Later relatively minor additions and corrections were made as part of the review process and these have been reflected in the units listed above. Further detail was considered only at the RCM assessment stage and these are shown in brackets above. A comparison of the FMECA and RCM physical models is included in Appendix B8.1.

Table 10 Units of the Physical Model

Foundations	**Columns and abutments**	**Deck**	**Fittings**	**Services**
Piles (cofferdam) Pier Abutment foundation	Column Deck main bearing Abutment structure Abutment drainage North bank traffic ramps	Box girders Composite slab deck (deck upstand) Girder diaphragms Expansion joint unit (north viaduct joint) Carriageway surfacing Footpath precast concrete slab Kerbs (kerb backing) Services bay White lining Manhole access to box girders Painting to box girders and diaphragms Girder restraints at column bearings Girder restraints at abutment bearings Bolted connections between box girders and diaphragms	Cathodic protection Anti-collision protection Footpath handrail (+ fixings) Parapet handrail (+ fixings) Traffic signs (variable signage) (+ fixings) Mobile under deck access platform (moving platform) (vertical access to platform) (motor for platform) Pedestrian lifts	Telecom cables Gully Gully drain pipe Emergency communications system (+ fixings) Weather stations (+ fixings) Lighting for traffic signs Lighting junction box Lighting column and fitting Lighting cable

3.2.4.2 The Tay Bridge Functional Model

Functional block diagrams, or functional flow diagrams (Blanchard and Fabrycky, 1990) are developed to 'structure system requirements into functional terms. They are concerned with *what* is to be accomplished, versus the realisation of *how* something should be done'.

The functions of each main physical element have been cross mapped so that an engineering understanding of the bridge is portrayed. The full model is in Appendix B3.

The model includes groups of structural, operation and maintenance, plus protection; with structural being the primary group. The system level FMECA prioritises availability or service levels while the unit level FMECA will primarily consider structural capability; both within a resilience framework for assessing the effects of hazards impacting on the bridge. This structure complements an asset management approach in that the intrinsic structural capability supports the resulting service level performance.

In terms of a recent water related resilience framework (UKWIR 2013), both assessments are bottom-up approaches in that they depend on detailed knowledge of the bridge structure, operation and maintenance.

3.2.4.3 System Level Functions and Failure modes

The system level FMECA function table below illustrates that the bridge has been viewed as a conveyance system with three main functions: to move vehicles; to move pedestrians and cyclists; and to supply services to and along the bridge.

This provides the skeleton or structure of the system level FMECA analysis.

Failure causes are then listed against each mode in Appendix B4.

Bridge functions which are outside the operational control of bridge management were initially considered but later excluded by agreement with bridge staff. This includes, for example, the passage of marine traffic.

Table 11 System level functions and failure modes

SYSTEM FUNCTION		Failure modes				
To allow the movement of vehicles from one bank to the other.		A1.1.1 2-way closure	A1.1.2 1 - way closure	A1.1.3 Capacity restriction	A1.1.4 Speed reduction	A1.1.5 Size restriction
To allow the movement of cyclists and pedestrians from one bank to the other		A1.2.1 Closure		A1.2.2 Capacity restriction		
To supply services along the bridge		A1.4.1 Breakdown		A1.4.2 Capacity restriction		

3.2.4.4 *Unit Level Functions and Failure Modes*

Four functions have been identified in the functional model in Appendix B3. Three main failure mode groups were identified which applied across the 4 functions and these informed the unit level FMECA.

Table 12 Unit level functions and failure modes

ITEM FUNCTION	FAILURE MODES		
Structural or load bearing function	Reduction of safety factor below design minimum	Physical collapse or complete breakdown	Deterioration beyond economic repair
To maintain long term durability in the face of environmental or physical threat			
To allow inspection and management			
To maintain safety and control for bridge users			

To avoid excessive complexity and timescale, only 1st level units of the physical model have been assessed in the unit level FMECA and no consideration has been given to a finer level of detail. FMECA is traditionally employed down to a fine level of detail but this is best suited to detailed analysis of particular troublesome elements or units where the staff time and effort could be justified. Again for time and cost efficiency, only the most likely failure mode has been listed for each unit. This has generally been either a/ for structural load carrying units, a reduction in load carrying capability to reduce the safety factor below that recommended by design codes (i.e. enough to prompt engineering staff to impose traffic restrictions) or b/ for mechanical units, a mechanical or physical failure. The failure modes are shown in Appendix B7.

This row by row assessment of physical unit and failure mode has been replicated for the RCM exercise, but with a range of failure modes being considered for each unit. The process can best be understood as invoking a greater degree of detail at each subsequent stage.

3.2.4.5 Failure Causes

The system level FMECA spread sheet in Appendix B4 identifies 43 possible failure causes, originating from a STEEPLE analysis. This was essentially a brainstorming activity but also drew upon the records of bridge restrictions. These categories were then reduced to environmental, human, maintenance related and socio-economic groups, for ease of use. This shows the results of the assessment of which causes were reasonably possible for each failure mode. The causes are selected for their effects on bridge operation (or service levels) and include, amongst others, high winds, traffic accidents, planned and reactive maintenance, and future traffic increases.

This forms the detailed layout of the system level FMECA analysis and is dependent upon a detailed knowledge of the bridge physical structure and operating arrangements. For instance; two-way traffic movement on a single carriageway is not allowed because lane widths do not meet current safety standards, even for temporary works. Causes are occasionally listed twice in the analysis where the outcomes might readily show scale differences e.g. a marine collision where the consequences could range from a ‘scrape’ to a structural collapse.

The unit level FMECA spread sheet in Appendix B4 lists 26 possible failure causes and, similarly, forms the basis for the unit level FMECA exercise. The causes are categorised into environment, human, mechanical, physical and electrical groups. Because failure modes show consistency across many of the units, this table relates causes to units (rather than failure modes). The causes are selected for their effects on particular units and include, amongst others, large tidal waves of tsunami or seiche form, corrosion of different types, malicious damage, water ingress and electrical failure. Attention to structural and mechanical functionality, as opposed to maintenance of overall service levels for the system level analysis, led to a slightly different group of failure causes at this level.

3.2.4.6 FMECA Risk Priority Numbers

The FMECA exercise prioritises threats according to a risk priority number (RPN) which is a multiple of the following three subjective judgements, each rating numbers on a scale of 1 to 5. The first measure is the (approximate) probability of occurrence within one of 5 bands. This is the approximate probability of the failure cause (hazard) occurring; otherwise known as risk according to the Health and Safety Executive definition (see glossary). Sufficient differentiation of RPNs is given by the five bands, which obviates the need to attempt accurate return periods between events, which would give an unjustifiable accuracy, given the available data. The second measure is a severity level i.e. a hazard scale, or consequence in terms of both human injury and duration of unavailability. The third measure is the likelihood of detection i.e. whether the failure mode (the consequence of the hazard occurring) is likely to be detected after it occurs.

Care in interpretation, and consistency in applying these rating numbers is critical to the direction, outcome and value of this study. Guidance is included in Appendix B5 and below. Inevitably some judgement is involved. Repeatability concerns have been reduced by practitioner consistency checks applied to the risk priority numbers i.e. self-checking that similar modes in similar situations achieve similar scores. Reproducibility concerns have been reduced by bridge staff reviewing the results.

Resilience is specifically addressed by:

i) Judging ‘probability of occurrence’ to take account of increasing, or decreasing risk in future due to climate or social change.

ii) Similarly, with the severity scale.

iii) Judging ‘likelihood of detection’ taking into account existing inspection and maintenance regimes. In other words, looking at the limits of these regimes and increasing the rating numbers where conditions or threats may remain undiscovered.

The third measure, likelihood of detection, is subtler than the other two and reflects the generally increased consequences of a failure mode if it is initially undiscovered. This is particularly pertinent with regards to a bridge where prompt discovery of a problem will lead to bridge closure and therefore maintenance of public safety. Preventative or precautionary work reduces availability, but with less social impact than would otherwise be the case, particularly if closures are managed to avoid peak traffic flow periods.

Standard guidance notes for rating are included in Appendix B5. An example of their application is given in sections 3.2.4.7 and 3.2.4.8. Particular notes on their application, largely relevant to the system level FMECA, are set out below.

PROBABILITY OF OCCURRENCE

Guidelines:

a. Existing control arrangements are critical; for example, the occurrence of ice and snow is taken to be the probability of these failure causes temporarily defeating the management arrangements of temperature monitoring, use of a snowplough and use of potassium acetate when low temperatures are forecast. This has been assessed as remote rather than probable because snow/ice which is managed by the bridge staff is not a failure mode; only when they result in unsafe conditions for bridge users do they become failure modes.

b. A judgement on the frequency of occurrence has often relied upon past records of disruptions to bridge traffic flow as a guide. In particular, the record of frequency and duration of historical stoppages has been used as guidance.

Future projections; long term but predicted events (e.g. sea level rise) are recorded as 2 (unlikely but possible in any year); long return period events either 1 (so unlikely that it can be assumed that it will not occur) or 2, dependent upon historic likelihood. This scoring regime does not depend on an accurate estimate of return periods (an accuracy which is often not justifiable).

SEVERITY LEVELS

Severity level descriptions consider two independent variables; human injury and duration that the bridge functionality is restricted or out of action. Environmental damage is not specifically included but can be allowed for in terms of the length of time the bridge would be out of use while environmental problems were dealt with.

In terms of the two independent measures contributing to the severity rating number, there are failure causes which can be high in injury and low in function impact (e.g. attempted suicides) and ones which are the reverse (e.g. unauthorised protests). Wherever the potential for injury and disruption leads to different ratings, the higher number of the two has been taken.

Guidelines:

a. For most failure modes there are a range of failure effects, measured in severity terms. Rather than list all possible effects, we have taken a view on the most likely. Sometimes two effects in the range are listed, mostly only one, rarely more than two.

b. Many police incidents take place on the bridge. These have been rated as 5 because a fatality could be involved. It is acknowledged that the incidence and severity of these is largely independent of management or maintenance arrangements on the bridge but there may be preventative measures which could discourage incidents of self-harm (e.g. netting above the parapet railings).

c. The severity level assumes normal bridge management arrangements are in place and effective e.g. for wind speeds in excess of 80mph when all traffic would be prohibited, a severity rating of 2 (restriction of bridge functionality for maximum of one day) has been selected as the historical duration of high wind speeds has generally been less than one day. If traffic had not been prohibited a rating of 3 or 4 would have been appropriate as injuries resulting from traffic accidents would have been likely.

LIKELIHOOD OF DETECTION

The definition of ‘detection’ has been taken as ‘detection that failure has occurred’ i.e. that failure would be noticed once it had occurred.

Guidelines:

Any natural phenomena which is monitored, or the consequences of which can be clearly seen, is rated as 1(control will almost certainly detect a potential failure mode). For example, as wind speed is monitored then detection of a trigger level is rated as 1.

a. Any problem or incident which occurs at carriageway level has been rated as 1 on the basis that CCTV cameras plus direct observation allows bridge staff a good oversight of what is happening. Operational guidance also requires staff to undertake more regular vehicular patrols in the event of a camera breakdown.

These guidelines lead directly to 4 of the top 5 risk priority number scores in the system level FMECA being for ‘below deck’ issues. Refer to section 4.3 for the highest scoring issues.

One measure of the flexibility of the FMECA tool is that ‘detection’ could be replaced by ‘prediction’. This would then score more highly those failure modes where prediction measures are not in place. To take the example of wind speeds: while we can score this as 1 under the ‘detection’ rule, this would likely move to 3 if likelihood of prediction was applied. Applying the ‘likelihood of prediction’ rule tends to prioritise low probability natural events, some of which may be more likely in future decades. This has not been followed through but may be of interest if reducing the cost implications of failure due to high consequence, low probability natural events is to be addressed. The ‘detection’ case doesn’t highlight natural causes of failure which are the unpredictable, ‘black swan’ (Taleb 2008) events with the potential to cause the highest failure effects.

3.2.4.7 System level FMECA example

The bridge operational functionality as a whole is under consideration, i.e. impediments to the bridge function as an overall asset. This can be regarded as an assessment of the resilience of the bridge. The failure causes are, generally, external constraints on the effective functioning of the bridge as a conveyance mechanism. In this respect the functional block diagram (appendix B3) is the starting point. Appendices B4.2 and B5.2 feed into the appendix B6 FMECA assessment and the relevant row is reproduced below.

Table 13 System level FMECA example

Item Id. No.		**A1**
Item Identification		Bridge
Item Function Id. No.		**A1.1**
Item Function		To allow the movement of vehicles from one bank to the other.
FF Id. No.		**A.1.1.5**
Failure Mode		Reduction in capacity by way of vehicle size limit
FC Id. No.		E1a
Failure cause		Wind speed 45-60mph
Failure Effects	Local Effect	Double decker busses prohibited
	Next Higher	Bus company reverts to single deckers
	End Effect	Bus passengers inconvenienced for, generally, a short period
Criticality Analysis	Occurrence	**4**
	Severity	**3**
	Detection	**1**
Risk Priority Number		**12**

Following through the process one row at a time, from top to bottom:

The item under consideration is the bridge as a whole. The function under consideration is the facilitation of vehicle movement. The failure mode (first visible manifestation of failure) is a limitation on vehicle size using the bridge. The failure cause is a moderate wind speed which results in the failure mode. There are then a series of failure effects, each leading on to the next and generally increasing in scale at each step. By this thought process the practitioner is driven to appreciate the 'chain of effects' which result from the failure mode. Note that when a 'chain of effects' is described there is consideration of a greater field of view at each step. This is in contrast to a timeline 'chain of effects' which would be characterised as consequences rather than effects.

Once there is an understanding of the end effect, it is simply a matter of applying the rankings listed in Appendix B5. The fairly broad range descriptions applied to the three rating metrics have the advantage of not requiring a precise quantitative calculation before scoring. Applying a precise number to say, the probability of occurrence can lead to a false sense of security in that it depends on the quality of the data used. It could also lead to the model results being too volatile if new data was considered.

The record of restrictions due to wind speeds in the range of 45-60 miles per hour over the 1999-2012 period results in a score of 4 for probability of occurrence. Reference to the same data shows that the duration of a vehicle size restriction for this wind speed tends to be no more than a small number of days. Therefore, the level of severity score is 3. Note that this is dependent on bridge operational protocols as listed in the wind speed thresholds included in table 7. For example, if double decker buses were not prohibited from travelling in this range of wind speeds then the scoring could be 5, assuming the potential for a bus to topple over. Therefore, the scoring is predicated upon the current bridge operational regime. It follows that changes to the operational regime can affect the risk priority number, which is as it should be.

The likelihood of detection score requires a judgement as to the likelihood of the bridge operational staff failing to register a high wind speed. As they have access to tailored daily weather forecasts, there are wind speed monitors on the bridge, staff are permanently based on site and undertaking regular patrols, it is considered almost certain that a wind speed of 45 miles per hour will be detected. So the score is 1.

Therefore, the risk priority number (RPN) is 4x3x1=12.

This number is a measure of relative importance in risk terms and allows the highest risk issues to be addressed to check if measures can be taken to reduce the RPN.

3.2.4.8 Unit level FMECA example

The approach of the unit level FMECA has a different emphasis from the system level, overall approach. The bridge physical model remains as before but the functional model is different (see Appendix 3) and the relationship between the two has a higher priority. This FMECA is a more conventional one and leads into the RCM exercise. Attention is focussed on each physical item in turn and the results are largely concerned with reliability.

Appendices B4 and B5.1 set the framework for the FMECA assessment. Appendix B4.1 now relates failure causes to items, rather than causes to modes for the bridge as a whole. Only one function and failure mode has been examined for each item; but a number of possible failure causes. There will in practice be subsidiary functions and failure modes but the resulting failures will be less serious therefore have been neglected in this assessment.

The functionality of each item is considered in turn and the failure causes include both externally acting (environment and human) and internally acting events or processes (mechanical, physical and electrical). The box girder item will be used as an example to describe the process and the relevant rows are reproduced below in **Table 14** Unit level FMECA Example.

Table 14 Unit level FMECA example

Table 13 Unit level FMECA example

Item ID. No.	Item Identification	Item Function ID. No.	Item Function	FF ID. No.	Failure Mode	FC ID. No.	Failure Cause	Failure Effects			Criticality Analysis			Risk Priority Number
								Local Effect	Next Higher	End Effect	Occurrence	Severity	Detection	
C1	Box Girders	S	Transmits deck loads to column bearings		Loading safety factor reduced below specified level		Large wave	lateral force breaks fixings at bearings	Deck is left skew/ joint is jammed	Deck is unsafe to use	1	5	1	5
							Air temperature or precipitation extremes	High temperatures cause closure of expansion gap	Deck buckles	Deck closed to traffic	1	4	1	4
							Corrosion	Structural section loses strength	Unable to support specified loads	Deck closed to heavy vehicles	2	3	2	12
							Fatigue cracking	Cracks appear at areas of stress concentration	Unable to support specified loads	Deck closed to heavy vehicles	2	4	4	32
							Heavier lorries allowed	Design check shows strengthening required	Strengthening works undertaken	New heavier lorries allowed to cross bridge	2	4	1	8

Following through the process one row at a time, from top to bottom:

The item under consideration is a representative box girder spanning between columns and supporting the bridge deck plus live loads. The function under consideration is the load carrying capacity of the girder. The failure effect varies with the cause (either a partial or complete traffic restriction) but the failure mode (first visible manifestation of failure) is taken to be a structural assessment by the bridge engineer which concludes that load carrying capacity fails to meet current codified standards. For each of the five failure causes there are a series of failure effects, each leading on to the next and generally increasing in scale at each step. The anticipated failure pattern or mechanism is described there. There is inevitably some judgement involved in the allocation of failure causes to each item shown in Appendix B4.1, but failure causes can be re-visited at any time during the life of the asset.

Once there is an understanding of the end effect, it is again a matter of applying the rankings listed in Appendix B5.2

In terms of probability of occurrence, a steel temperature above 32 degrees centigrade (the upper limit for the calculation of movement joint gaps) in this temperate coastal location has been judged improbable in table 1 of Appendix B5.2. Similarly, the occurrence of a wave high enough to impact the deck has also been judged improbable. There is evidence of a flood wave at Dundee harbour in the 1700s but the return period is likely to be long. Both of these failure causes are scored 1.

Corrosion is an ongoing process but the frequency of inspection and level of ongoing minor paintwork repairs means that, in any one year, the probability of corrosion advancing quickly enough to reduce the girder carrying capacity sufficiently to cause imposition of a weight limit must lie between ‘once a year’ and ‘so unlikely it can be assumed it will not occur’(again to the table 1 bands in Appendix B5.2. So that failure cause is scored 2. Fatigue cracking follows a similar logic. The imposition of heavier lorry loads has already occurred during the life of the bridge and may happen again as vehicle technology advances.   So it would seem eminently likely that this may happen again; but not every year. So that is scored 2.

In terms of level of severity scores; these are more uncertain in that there is a range of scale and impact for any of the causes. The scoring here follows the logic below.

A large wave is likely to be sudden and unexpected. The likelihood is that the bridge would be open to traffic at the time. Fatalities would almost certainly result therefore a 5 is appropriate. Corrosion rates would almost certainly be monitored and repairs or the imposition of a weight limit could be planned for. There is unlikely to be a complete closure of the bridge. Owing to the long planning time involved, it has been estimated that an engineered repair scheme could be undertaken in days rather than weeks so this has been scored 3. Following this same logic, both short term high temperatures and the discovery of fatigue cracks are likely to lead to emergency weight limits with a longer repair time hence are scored 4. If legal weight limits are increased in future the effect would be to require major strengthening works with significant periods of weight restriction therefore is scored 4.

In terms of the likelihood of detection; again this is defined as 'the likelihood of detecting that failure has occurred'. Girder movement or buckling could not pass un-noticed where permanent staffing arrangements are in place. They are scored 1. The imposition of heavier weight limits is similarly 1. Corrosion is such a slow steady process that it is unlikely that regular inspections will miss this so a score of 2 has been assigned. Cracks caused by fatigue are harder to detect and can occur over a shorter timeframe – i.e. they could occur between inspections. This could be a 3 or a 4. A 4 has been allocated meanwhile but targeted inspections to particular areas of risk such as points of contra flexure where girders are continuous over the navigation piers could reduce this to a 3 or even a 2. This would reduce the high risk priority number to a 24 or a 16.

3.2.5 RCM Methodology

3.2.5.1 General

The RCM methodology analyses the consequences of each failure mode from the unit level FMECA exercise, “and identifies an applicable and cost-effective maintenance regime. It does so using the principle that a maintenance task is worth doing if it deals successfully with the consequences of the failure mode which it is meant to prevent” (Kumar et al, 2000). The approach is based on a decision logic process set out in the logic paths included in Appendix B8. The overall objective is to identify which maintenance tasks are unnecessary because they are only needed for aesthetic purposes, or they are ineffective in reducing failure risk.

The primary purpose of this ILS tool is to reduce maintenance costs by adopting the right maintenance regime, while meeting health, safety and environmental standards and while meeting economic, operational and appearance requirements. Where selection of a maintenance regime is insufficient to meet the standards, as can be the case for enhanced resilience needs, then a redesign or engineered improvement will be the required outcome of an RCM exercise.

The RCM exercise can be split into three steps: step A implications of functional failure, followed by step B selection of inspection task, then step C selection of repair task.

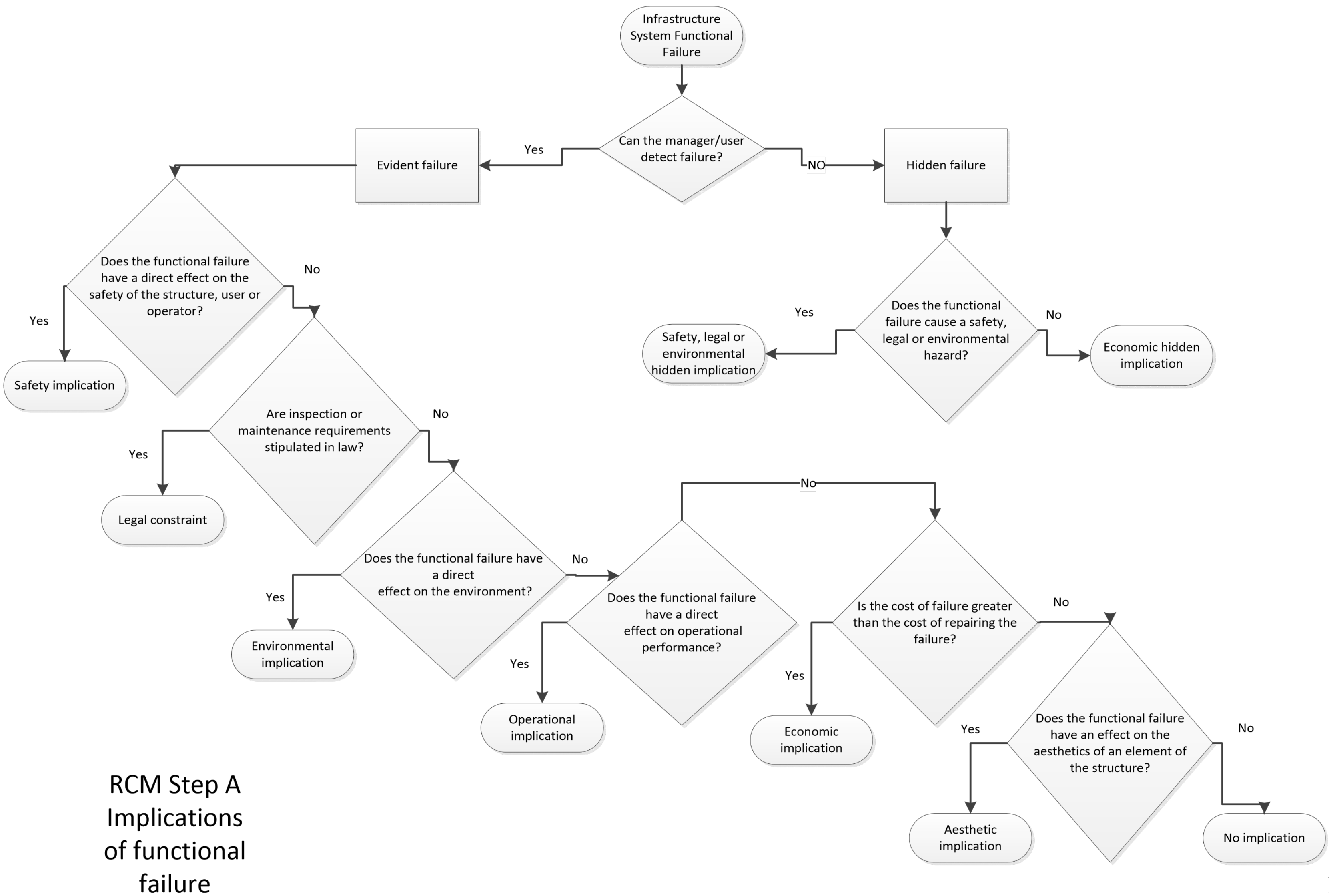
STEP A: IMPLICATIONS OF FUNCTIONAL FAILURE

The flowchart setting out decision steps is included in Appendix B8.2 and figure 10 below. The seven consequence classes are described below, in order of importance:

M1 Safety and health for users and operators: any failure mode with the potential to cause death or harm of a person, either from structural failure or a dangerous incident.

M2 Legal obligations to inspect the asset or part at set intervals.

M3 Environment: any failure mode which results in environmental damage, e.g. air or water pollution.



Infrastructure System Functional Failure
Can the manager/user detect failure?
Yes
Evident failure
NO
Hidden failure
Does the functional failure have a direct effect on the safety of the structure, user or operator?
Yes
Safety implication
No
Are inspection or maintenance requirements stipulated in law?
Yes
Legal constraint
No
Does the functional failure have a direct effect on the environment?
Yes
Environmental implication
No
Does the functional failure have a direct effect on operational performance?
Yes
Operational implication
No
Is the cost of failure greater than the cost of repairing the failure?
Yes
Economic implication
No
Does the functional failure have an effect on the aesthetics of an element of the structure?
Yes
Aesthetic implication
No
No implication
Does the functional failure cause a safety, legal or environmental hazard?
Yes
Safety, legal or environmental hidden implication
No
Economic hidden implication
RCM Step A Implications of functional failure

Figure 10

E1 Operational: any failure mode with the potential to adversely affect the operational performance of the bridge systems or serviceability of the bridge elements.

E2 Economic: any failure mode with the potential to incur a significant economic effect due to the cost of maintenance or repair. This includes direct costs to the Bridge Board, e.g. for bridge repairs, in addition to wider societal costs, for example due to traffic diversions. If the cost of failure and its consequential damage is greater than the cost of preventing the failure, then preventive action is worthwhile.

L1 Appearance: any failure mode with the potential to adversely affect the aesthetic quality of elements of the bridge.

L2 No significant consequence.

Group **M** – it is mandatory to act to avoid failures.

Group **E** – actions to mitigate failures are to be based upon lowest overall cost maintenance regime. Costs are to include wider societal costs of failure.

Group **L** – consequences are of low significance.

Guidance notes for selection are listed below:

1) The 7 classes are a hierarchy inasmuch as priority should be given to the category mentioned nearest the top of the list e.g. if **M1** and **E1** can both apply to any failure mode, include it as **M1**. The exception is the **E1/E2** choice where selection depends on which one is a more important consequence, in the judgement of the engineer. Operational consequences have been prioritised meanwhile as this is expected to be the Bridge Board's priority.

2) The most severe direct consequence is selected. For example, steel painting could be allocated to an appearance consequence whereas, in time, there is obviously a safety consequence. For this study the safety consequence applies. There is a case for dividing the RCM rows into a range of different scale failure modes, possibly related to bridge

condition grades, but this has not been undertaken at this stage. Refer to the notes on the spread sheet where high uncertainty exists.

3) Whether failure is hidden or evident can depend on the cause of failure mode. For example, corrosion in columns might not be noticed (unlikely, due to cathodic protection system) whereas the effects of impact damage on a parapet rail almost certainly would be. If there is a good chance of a hidden failure, it has been recorded as such.

4) What is failure? Moubray (1997) defines 'functional failure' as 'A state in which a physical asset or system is unable to perform a specific function to a level of performance that is acceptable to its owner or user'. This has been defined as when the structural load carrying safety factor is reduced so far that the bridge manager, on the advice of the bridge engineer, decides to place restrictions on (or close the bridge to) users. In other words, **Functional failure occurs when informed engineering knowledge judges that it is no longer safe to continue the full availability of the bridge for public use.** This is a useful definition but has had to be supplemented by the three definitions below.

5) Failure can be defined in three ways (El-Haram, 1995).
i) an element has suddenly become completely inoperable and can no longer perform its required function(s)
ii) an element is still operable but incapable of fulfilling some or all of its intended functions at the level of performance originally specified
iii) an element has gradually deteriorated to an unsatisfactory level of performance or condition, and its continued operation is either unsafe, uneconomical or aesthetically unacceptable.

6) Definitions (Moubray 1997): Evident failure – a failure mode that will on its own become evident to the operating crew under normal circumstances. Hidden failure – a failure mode that will not become evident to the operating crew under normal circumstances if it occurs on its own. Mowbray selects categories assuming the absence of an inspection regime as the thrust of his exercise is to define a regime from basic principles.

7) Given notes 4 and 5, many failures are hidden. If failure was to take the form of a collapse, then most would be evident. For reinforced concrete where corrosion or impact damage would be necessary then surface crazing or rust would be evident therefore deterioration would be evident but not necessarily at the point of failure. However, investigation would be prompted prior to the failure point. Therefore, for publicly visible reinforced concrete, failure has been taken as evident.

STEPS B & C: SELECTION OF INSPECTION AND REPAIR TASKS

The flowchart setting out decision steps is included in Appendices B8.3 & 4 plus figures 11 and 12 below. The selection hierarchy in this case is condition based maintenance, time based maintenance, then either re-design or reactive maintenance.

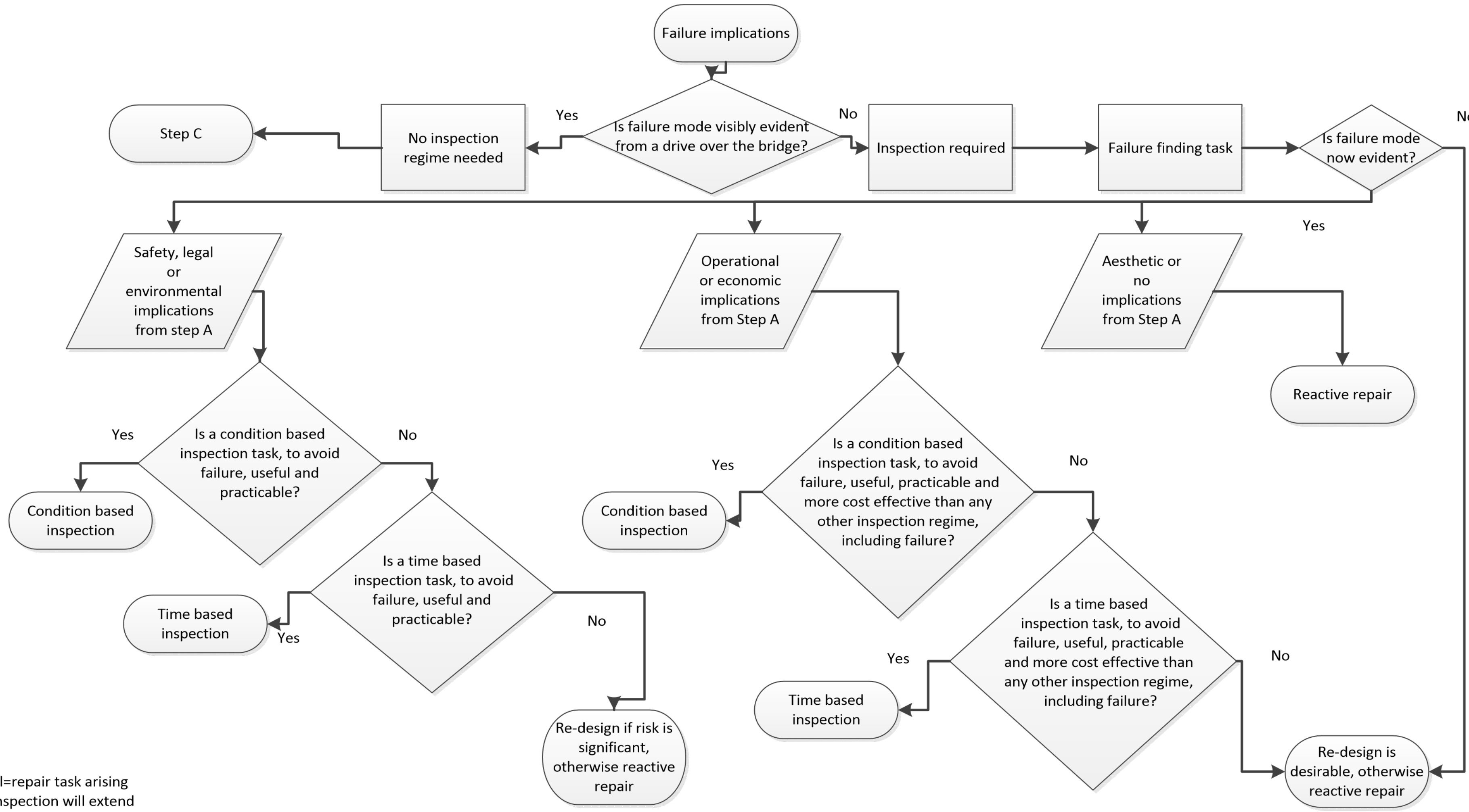
The ‘practicability of condition based maintenance’ hinges on whether deterioration along the time-line to failure can be assessed. This has been taken to be affirmative for reinforced concrete, for example. This is a critical judgement in defining the type of maintenance task.

The application of RCM to a major bridge has been tailored in two respects:

i. The costs incurred in inspections can be high and warrants separate consideration. In addition, reactive maintenance still requires time based inspections. Also there are legal requirements which govern some inspection intervals, for example for lifting equipment. Indeed, inspection regimes are essential to protect management against legal action in the event of catastrophic failures.

ii. There is normally an economic ‘test’ applied to the choice of a condition or time based maintenance regime i.e. are the overall costs worthwhile in comparison to the option of doing nothing (replace on life expiry rather than repair). In the case of this bridge it has been assumed that at this stage of its life the economics will favour the repair option. This also meets public expectations.

In practice, the same unit has a number of possible failure modes; therefore, a range of maintenance regimes for any unit can be appropriate.

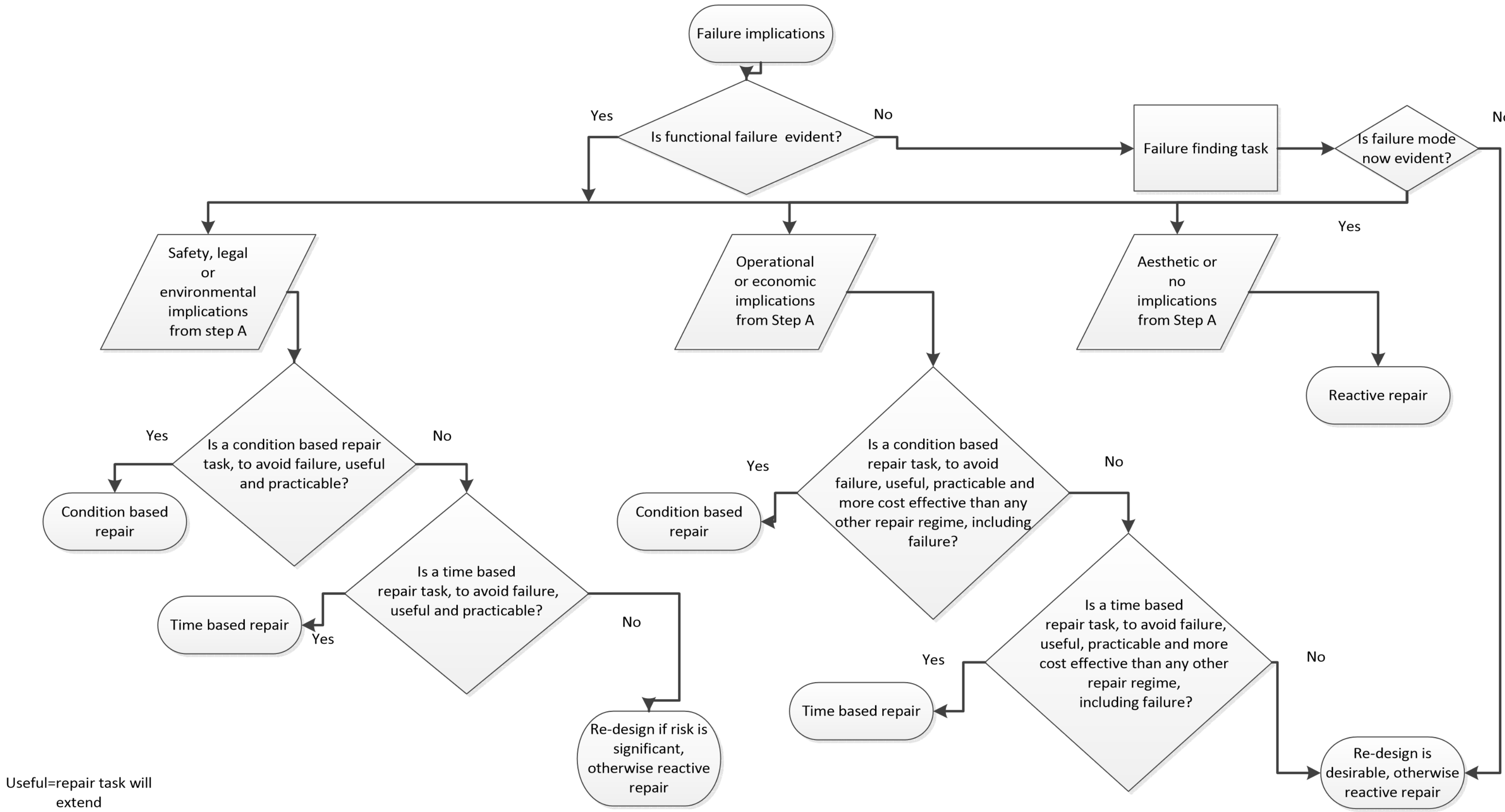


Useful=repair task arising from inspection will extend functional

RCM Step B

Figure 11 Inspection Task

Selection Flowchart, based on failure modes.



RCM Step C

Repair Task

Figure 12 Selection Flowchart, based on failure modes.

The general selection guidance is summarised below:

Table 15 RCM Inspection and Maintenance Task Guidelines

TYPE OF DETERIORATION MECHANISM	TYPE OF INSPECTION REGIME	TYPE OF ACTIVE TASK NEEDED
Measurable, predictable, medium to long term interval between failure mode and failure function points	Time based prior to failure mode; condition based after.	Condition based repair
Unpredictable, short term interval between failure mode and failure function points	Time based; owing to 'random failure' nature.	Reactive repair or replacement
Frictional degradation (i.e. mechanical wear and tear)	Time based - generally legal requirement for access and lifting gear	Time based – e.g. greasing or similar
Age related deterioration of electrical units	Time based; increasing frequency with age	Time based repair or replacement

3.2.5.2 The Tay Bridge RCM application

Whereas the FMECA assessments are intended to identify and protect against failure causes, the RCM assessment is geared towards identifying effective and efficient maintenance regimes. The RCM takes the unit level FMECA as the starting point and considers each unit in turn. The example uses the box girders again and both tables below show the workings for only that unit. The methodology and principles are the same for all the other units.

The RCM assessment has considered functionality and failure modes to a higher level of detail and multiplicity than the unit level FMECA. This has been done in order to more fully understand these properties of each unit. The resulting cross mapping of functions and failure modes consequently appears complex and there have had to be reversions to dominant types at stages in the process.

Appendix B8 shows decision diagrams for guidance. Appendix B8.1 is the RCM spreadsheet for the bridge units. Appendix B8.6 is a diagrammatic representation of the structural load paths through the bridge. There are usually two steps to an RCM assessment, which lead to a recommendation for a maintenance regime type. Due to the relatively high expense of inspection alone on this civil engineering asset, a 3rd step has been introduced i.e. inspection and repair have been separated. Appendices B8.2, B8.3 and B8.4 show the 3 steps in isolation and B8.5 shows how they link together.

The RCM requires decisions to be made on the basis of both functions and failure modes for each unit to be maintained. The functions and failure modes do not directly map across to each other, although there are many cross links, which is why the spreadsheet considers both separately and is ‘hinged’ in the middle at the black column in Appendix B8.1. Both parts are shown separately in the two tables below.

While the flow charts show the hierarchical decision making process, the tables show simplified questions in the headings and describing the process below will aim to clarify and explain.

Table 16 – RCM step A; Selection of failure consequence

Subsystem	**Unit**	**Primary functions**	**Function service level or performance**	**Functional failure (consequence of failure mode)**	**Impact of functional failure**	**Implication of functional failure**
Superstructure: deck	Box girders	To span between column bearings	Limit deflection to design limits	Deflection greater than design limits	Weight limit imposed	Operational
		To carry bridge loads and distribute to column bearings	No visible corrosion or cracking	Load carrying capability of box girder is reduced such that the factor of safety is reduced below an acceptable limit	Weight limit imposed	Operational
		To allow internal access	Safe and ready access	Interior is unsafe for humans	Additional precautions required prior to access	Economic

Table 17 Example of RCM steps B & C

Table 16 - steps B & C													
Key: N = No; Y = Yes; O = Operational; E = Economic													
Failure modes	Inspection evaluation - step B					Maintenance intervention - step C							Proposed task
1st visible physical manifestation of failure	Can normal attendance of management detect failure?	Inspection regime required?	Can progress of deterioration be measured?	Time based	Condition based	1st hierarchical implication type	Can progress of deterioration be arrested prior to functional failure?	Condition based intervention	Time based intervention	Re-design	Reactive		
Pitting of steel	N	Y	Y		Y	O	Y	Y				Condition based inspection frequency with local repairs	
Cracking of steel	N	Y	Y		Y	O	Y	Y				Condition based inspection frequency with local repairs	
Flaking of steel	N	Y	Y		Y	O	Y	Y				Condition based inspection frequency with local repairs	
Deformation	N	Y	Y		Y	O	Y	Y				Condition based inspection frequency with local strengthening	
Poisonous internal atmosphere	Y	N	N/A			E	N				Y	Atmosphere tests before entry	
Weld weaknesses	N	Y	Y		Y	O	Y	Y				Condition based inspection frequency with local strengthening	
Shear connector weakness	N	Y	Y		Y	O	Y	Y				If non- destructive testing is available then implement, followed by condition based maintenance; otherwise opportunity testing	

For the girders, 3 primary functions are identified in table 15; the abilities to span between columns, carry load and allow access for maintenance. Required service levels and failure levels are identified for each of the three. The impact or consequence of failure is listed. This is again predicated on current bridge supervision levels. For example, if the load carrying vulnerability of the girder was not recognised and a weight limit imposed then there would be a safety implication. There are two operational and one economic implications for this unit and the one which links most directly to the steps B&C failure modes is selected in that process. For example, the failure mode of an internal poisonous atmosphere has an economic implication in table 15; following on from the function of allowing internal man access.

Seven likely failure modes are identified in table 16. For each one, the steps in Appendices B8.3 and B8.4 are followed. For example; the steel pitting failure mode. Normal visible assessments cannot be made inside the girder so specific inspections are necessary. The slow and predictable progress of deterioration can be monitored between inspections so a condition based inspection interval is applicable i.e. more frequent inspections for severe cases. For similar reasons, condition based repairs are appropriate.

In practice, any one unit may have a number of failure modes, some of which can have their deterioration monitored and some not. In other words, they can fail due to either slow deterioration mechanisms, (e.g. corrosion) or fast failure mechanisms (e.g. impact). The dominant task for the girders however is a condition based regime and this is transferred to line 3.1 in the RCM summary table in section 4.3.3

4 Results

4.1 Stage 1: Cross sector asset management study

4.1.1 Transportation sector

This can be subdivided into road, rail, water and air transport.

Roads - There are a number of guidance publications in this area (County Surveyors Society 2004, CIPFA 2010, UK Roads Liaison Group 2005) but implementation of guidance and recommendations is mixed. A view of this sector shows that asset management (AM), while developing, is not of central importance. Glaister et al (2009) indicates that the roads sector is a utility in need of a strategy. Certainly there is limited penetration of an asset management (AM) culture so far.

The UK highway authorities can be split geographically and in terms of the asset ownership. Trunk roads are the responsibility of the Department for Transport in England and Wales; Transport Scotland in Scotland. Remaining public roads are the responsibility of councils. AM thinking and dissemination through the organisations are notably further advanced within the trunk roads authorities. Amongst the councils the picture is very mixed: some have advanced the production of plans far enough to encompass roads within sectors encompassing other assets (e.g. property and parks) while others have barely started on addressing data capture requirements associated with asset management plans (AMPs). Progress may be slightly behind in Scotland generally although the mixed picture makes it hard to be definitive as any council to council comparison will not show the national picture.

A detailed comparison of the highways and water sector follows in 4.2 but this sector lags the water sector generally due to: the lack of competition and the absence of the commercial focus of a regulator plus the indirect commercial relationship with road users. There appears to be less recognition of the potential benefits of the application of asset management principles, perhaps coupled with staff shortages impeding implementation.

Rail – The UK rail industry owns many of the oldest civil engineering assets in the country, many of which date from the middle of the 19th century. Many of these have indeterminate life characteristics (e.g. earth embankments and cuttings plus masonry bridges and culverts) where maintenance is critical in deferring the need for replacement. This industry is therefore particularly suited to the application of ILS and AM. The 2010 Mouchel paper by Stratford et al indicates evidence of ILS application to AM in the rail industry. The 2011 Institute of asset management (IAM) paper by Kirwan & Newby also indicates that AM principles and techniques are in use. The Office of the Rail Regulator (ORR) have accepted in 2008 that Network Rail have a compliant asset register. A Network Rail AMP or AMPs do not appear to be completed yet (Arup 2011,1.1.13) therefore a direct assessment of this has not been possible. The Arup report notes that Network Rail are preparing 300 AMPs, one for each UK strategic route. The same report (1.1.14) recommends the use of FMEA for asset assessment and makes some comparisons with the Highways Agency and London Underground asset management. A similarly recent report (Atkins 2011) reports uneven AM practice across the company and claims potential savings of up to £400 million if asset management techniques were fully applied.

The Office of the Rail Regulator does explain how asset management progress is monitored, as below.

"*An asset management assessment framework forms the basis of the on-going development and improvement reviews carried out by the ORR to ensure that Network Rail complies with licence condition 1, asset management. In summary, the framework considers Network Rail's asset management performance, capability and maturity in the following 6 areas:*

- *Strategy & Planning*
- *Whole-life cost justification*
- *Lifecycle management & delivery*
- *Asset knowledge management*
- *Capability development*
- *Review & improvement*

With regard to Network Rail's asset information strategy, the ORR and the part B (Asset Management) Independent Reporter monitor asset systems and data through regular *auditing.*

The ORR retain a list detailing the development and improvement recommendations from the audits.

The ORR is monitoring Network Rail's asset information strategy. We review progress on a regular basis to ensure that Network Rail is making progress to achieve appropriate asset systems and data for the business and in particular for good asset management."

In conclusion, it appears that Network Rail is making efforts to drive an asset management approach but the scale of the task is making this a slow process.

Ports authorities – Neither Forth Ports nor Associated British Ports indicate any asset management information on their websites.

British Waterways Board: No detailed guidance is available from their website but they appear to implement some asset management principles in their 'steady state' spending prioritisation model which takes into account customer service standards, deterioration levels and failure risks. Service standards are detailed, and monitored by an advisory panel selected from canal users. Complaints are taken into account in setting these standards. There are also other user group panels and forums, with different priorities. Operational risks and priorities include the need to ensure sufficient water supply, dredging of sediment, vegetation control, litter control and safety for staff and public. They have an asset inspection system with condition based targets. There are specific customer surveys but nothing mentioned about surveying customer assessment of infrastructure condition. They have only just started allocating ongoing maintenance funds on the basis of condition improvement needs (core waterway programme in their 2011/12 corporate plan). Major works funding is prioritised on a risk basis. Infrastructure condition is planned to be held at a steady state (corporate plan 4.2). The corporate plan makes no mention of introducing an overall asset management plan in the near future. The organisation is planning to split into two entities, with the English and Welsh entity looking to achieve charitable status. Currently the single organisation is responsible to (and funded by) the Scottish Government in Scotland and DEFRA south of the border.

British Airports Authority: Their capital investment plans (CIPS) are publicly available and split according to airport. The Heathrow airport CIP 2011, for example, includes major expenditure programmes, which are regulated by the Civil Aviation Authority. While there is evidence of scrutiny of programmes, and the CAA requiring evidence of customer feedback and views over facilities, there is no mention of an overall asset management planning style approach to identifying expenditure requirements.

Manchester Airport: Their master plan to 2030 makes no mention of a clear asset management approach to maintaining assets.

4.1.2 Water sector

This UK sector can be split geographically at the England/Scotland border. Southern private water companies have defined geographical areas and are regulated by the Office of the Water Regulator (Ofwat). Scotland has one public sector water organisation which is monitored by the Water Industry Commissioner for Scotland (WICS). Apart from the lack of competitors, and the public ownership of Scottish Water, this organisation does seek to emulate, and compare favourably with, the private English and Welsh companies.

While AMPs are not separately published by the water companies, AM is considered so important by Ofwat, and is therefore so central to their organisations that much detail is included in their business plans for the 5 year review periods. More detail is included than is available for other infrastructure sectors and this reflects how seriously AM is taken by the water industry. Ofwat have measured water company progress in asset management techniques since 2004 (Deadman). They consequently appear to be vigorously implementing AM, while being slightly behind Ofgem regulated companies (see 4.1.5). There are few clues as to the prevalence of ILS use though.

Particularly impressive are the measures taken to solicit and incorporate customer views, plus the integration of data management systems with asset deterioration modelling. Progress in these areas is driven by competition between the companies to avoid the regulator imposing budget penalties. Asset management philosophy and techniques are regarded as fundamental to their business model and their commercial success.

Specific aspects of AM implementation in the water industry, compared to the roads sector, are covered in 4.2.

4.1.3 Energy sector

A literature search of documents relating to asset management implementation has been largely unsuccessful in uncovering publicly available AMPs in this sector. However, many maintenance plans are freely available and some of these are listed in Appendix A1. Secondary sources have been useful in giving an overview of the industry and the Institute of Asset Management textbooks by Deadman and Lloyd have been especially useful.

Ofgem have required the electricity and gas supply distribution and transmission companies' asset management capability to be measured since 2002 (Deadman). In 2006, Undertakers agreed to report progress against PAS55(2004) requirements (Deadman). All regulated companies were certificated to this standard (since 2008 – Lloyd) Scottish Power was the first to be accredited to the later 2008 edition PAS, in March 2009. This utility sector accordingly seems to be furthest advanced in AM implementation, albeit details of specific company systems are difficult to access.

Oil: The oil and gas exploration and production sector is credited (Lloyd) with originating much of the thinking behind asset management and PAS55. No AMPs have been located but Lloyd chapter 2 goes into detail about how the oil resource companies in the North Sea during the 1990s achieved a step change in efficiency gains through devolving decision making powers back down to smaller units, each of which in Shell's case, has an Asset Reference Plan (ARP). A more detailed description of the development history of ARPs is given by Al-Hajj and Al-Saadi (2002).

Gas: Deadman's UK experience has been that 'the gas (supply) industry pioneered the adoption of many modern asset management techniques, such as a requirement for asset registers, asset risk modelling, 'no-dig' street working techniques and customer billing and trading systems'. Their lead in this field was attributed to the high safety requirement as well as the relative simplicity of their networks and capital works. The dissemination of these techniques into other utility sectors was through 'the movement of gas industry staff into other utility industries and the shared use of contractors'.

Wind and Wave power: This is a less mature industry and less system based than the main supply and distribution utilities. It has been shown (Andrawus 2008) how asset management, FMECA and RCM can be applied to optimise maintenance of wind turbines. It is stated that the wind industry lacked an asset management framework in 2008 so, unless dissemination through the industry has been rapid, it is likely to be fairly lightly developed so far.

Electricity: No AMPs have been located but the Ofgem remarks, above, apply. The National Grid Annual report and Accounts for 2010/11 includes an objective of executing best practice initiatives e.g. asset management but makes no other specific reference to asset management. Interestingly they have also tested their network resilience against climate change scenarios published by the UK government.

Nuclear: No AMPs located but this sector is a world leader in risk management, for obvious reasons. Hezoucky in IAEA-TECDOC-1590 gives a good description of RCM which has been used, in conjunction with FMECA, in the industry since 1984. EDF state that they have developed the use of RCM since 1989.

4.1.4 Communications sector

BT's Annual Report 2011 makes no specific reference to asset management. The Ofcom website has no headline interest in the subject either. BT staff are not listed attendees at recent IAM conferences, either as speakers or attendees. The inference is that BT is more concerned with new technology than maintenance of fixed assets. A similar narrative can be applied to the cable company Virgin Media. Again there may be evidence 'buried' in maintenance/operation manuals but the lack of visibility at annual report level would tend to limit the business priority of asset management.

4.2 Stage 2: Comparison of water and road sectors

4.2.1 Features of water AMPs

1/ An AMP is fundamental to their business model.

2/ The budget is adjusted by the regulator's view of their AMP quality.

3/ Targets are set by an external regulator.

4/ There is a threat of competition to their customer base.

5/ There is more customer input to define priorities.

6/ Service levels are more prominent.

7/ Tools and thought processes are more advanced.

8/ More staff resources are devoted to the AMP production.

9/ Companies are closer to a sustainable economic state: i.e. asset serviceability is steady.

10/ There is more vertical visibility of drivers and service levels.

11/ Resilience actions and climate change thinking is more detailed.

12/ AMP practice is generally embedded within their working practices.

4.2.2 Features of road AMPs

1/ Business drivers for AMP implementation are much weaker.

2/ There is less customer consultation and input into service levels.

3/ Expenditure is more budget constrained: maintenance plans are based on the available budget rather than the budget being built up from detailed needs and they are able to repair worst cases only. An exception is Hertfordshire council who appear to be more advanced in their thinking.

4/ The asset inventory is less accurate, with greater gaps.

5/ There is more scope for upwards integration into transport plans or general public service/environmental improvement plans. The Highways AMP can sit as part of a family of plans.

6/ The AMP practice is not generally embedded

4.2.3 Cross border water company comparison

1/ The Anglian Water (AW) report is much more detailed than the Scottish Water (SW) one and shows evidence of being further advanced. They started the asset management process earlier.

2/ SW are not directly competing with other companies in a commercial sense and reporting shows less evidence of ‘bursting to demonstrate capability’.

3/ Customer consultation: impressive evidence from AW and less detail from SW.

4/ SW strategy is to continue on their learning curve so they're in the upper quartile of the English and Welsh companies. The AW strategy is more focussed and clearly lists risks to future performance.

5/ AW objectives are to maintain service levels at least cost. SW objectives are to tackle performance improvements; reflecting the different maturity stage the companies are in.

6/ SW contingency planning is about combatting flood and drought. The AW equivalent is to design the capital programme to meet operational risks. They also make allowance for resilience and redundancy.

7/ Liaison with customers: SW monitor complaints and issue questionnaires. AW have various 'focus groups' of different types – a deep regime of customer consultation which then clearly impacts on their strategy/tactics.

8/ Documentation: not enough detail to compare in earnest

9/ Risk assessment methodology: there is much more detail available from AW, who mention pipe deterioration models, service impact modelling, main burst predictive modelling, split between service levels and physical problems. They also include an element for social costs. Polynomial regression modelling is used. Economic replacement ages are modelled. The SW plan mentions none of these.

10/ The AW capital plan is modelled by way of iterative runs of options. The SW plan is merely concerned with improving service levels.

11/ Both organisations have listed business/financial risk items.

12/ Methodology for accounting for asset depreciation: neither are clear on detail (e.g. will CIPFA guidance be implemented?)

13/ AW have correlated their failure models with reality and have meshed them with service level needs. There is no indication that SW have done this.

14/ Both have forecast future risks going forward. One example of SW having more autonomy might be their proposal to charge customers on a drained area basis. AW are probably constrained by Ofwat in this respect.

15/ Investigation of asset related failures: AW state they feed the results back into the deterioration models. There is no mention that SW does this.

16/ Continuing improvement: SW looking to try electric and heat generation on their sites. There is no mention of this from AW.

17/ Contingencies/management review: SW have on-going supervision over a programme of ill-defined work. There is nothing equivalent mentioned for AW.

4.2.4 Comparison of trunk roads and local roads

1/ Specifically Transport Scotland (TS) and Highland Council (HC) asset management plans are compared. Both have the potential to widen and raise the scope of the AMP: TS to include other transport modes (rail/air/water) and HC to include other physical stock which they manage. HC also have a corporate asset management plan. Both are first attempts with no further publication yet. TS will develop a work plan and finance plan following from capital works derived through this AMP.

2/ TS will generally delegate more duties on a long term basis (to the operating companies) than HC.

4.2.5 Detailed comparison of Scottish Water and Transport Scotland

1/ The AMP for Transport Scotland (TS) deals with roads and bridges only. In common with the councils, there is scope to expand the AMP to cover at least the whole road system, arguably even the whole organisation and what it's responsible for. The Scottish Water (SW) AMP, in common with other water companies, deals with the whole of the company's remit.

2/ The TS document is a first attempt and sets out what the intentions are with regards to implementation. The SW document has a lot more detail and history behind it.

3/ For TS, government sets overall policy. The same is true for SW but it and its regulator seem more at arm's length from government and it seems to have more scope to set a direction for the AMP/business plan. The TS one suffers more from 'government speak' in that it refers to other government reports more frequently; i.e. it's more enmeshed with government.

4/ Measurement of progress is set by TS; for SW it is set by the regulator. There is less evidence of external control and pressure on TS to meet performance standards.

5/ SW objectives are detailed, measurable and many are driven by legislation. TS objectives are aspirational and the routes to achievement are unclear.

6/ SW don't actually have an AMP: we're just looking at the business plan, i.e. a similar situation to the water companies in England and Wales.

7/ Delegation of responsibilities for action: TS delegate much of theirs to the operating companies (regional contractors). SW have more direct operational control as operational staff are directly employed.

8/ Contingencies/future risks: TS don't mention controlling demand or climate change, for example. SW is further advanced.

9/ TS have a need to filter down learning to councils in due course: so there's a level of dissemination both above and below its level.

10/ Both organisations have improvement plans in place to address AM gaps.

11/ Both organisations have customer surveys but the detail is not set out.

12/ Information management: there is a strong sense that TS have more work to do in pulling together the data in an AM form.

13/ Neither of them go into risk assessment methodology so a comparison is not possible.

14/ Life cycle activities: there is not enough detail on the basis of valuation so it is not possible to compare with CIPFA guidelines or each other.

15/ Monitoring and condition data production: TS have the advantage that most of their condition data, certainly carriageway condition is complete. SW condition data for underground assets is not directly gathered but based on sampling and extrapolation.

16/ Investigation/rectification of failures: both have high public visibility but road failures have marginally higher profile.

17/ Audits: TS pay for audits of the operating companies by an independent Performance Audit Group (refer to their 2010-11 annual report). SW is audited by the Water Industry Commissioner.

4.3 Stage 3 results

4.3.1 System level FMECA

An FMECA exercise has been undertaken for the bridge at two levels of detail, in order to assess both overall resilience and unit reliability. A system level or resilience FMECA was attempted first, which treats the bridge as a whole unit and essentially considers failure or diminution of service levels.

A drawback of any FMECA analysis is the cost of staff time involved in carrying out the exercise to completion. There either has to be a clear opportunity for cost saving or risk reduction or resilience gains; or there needs to be prior guidance given as to what level of application (system or unit level) is appropriate, or prior guidance as to which elements of the structure need to be examined in detail. The twin level approach used here examines hazards or failure causes affecting both asset and service failures and is considered the minimum necessary in order to be able to consider all major failure causes.

While the generic guidance in Appendix B5 suggests risk priority numbers (RPNs) of up to 30 are of little consequence, a lower threshold of 12 is used in this study to increase the size of the list and to allow better contrast with the highest scoring RPNs from the unit level FMECA exercise.

For the system level FMECA, there is a consistency within the highest scoring failure causes across many of the functional failures. Although frequency and severity may vary for the same cause but different functions, the highest overall scores include:

1/ Failure function E8b: River bed scour undermining piers remote from navigation channel.

2/ Failure function E1a: Wind speeds of 45-60mph lead to prohibition of double decker buses.

3/ Failure function M3d: Seizure or other failure of major joint or bearing causes emergency reactive maintenance to close bridge to traffic while lengthy repairs are made.

4/ Failure function M3c: Consequences as above but due to failure of other mechanical component

5/ Failure function H4: Police restrict traffic movement while investigating incidents.

4.3.2 Unit level FMECA

All the unit level FMECA results are in Appendix B7.

The highest scoring RPNs include:

1 Failure function A2: River bed scour undermining piers remote from navigation channel

2 Failure function C1: Cracking to box girders, due to fatigue

3 Failure function C3: Cracking to girder diaphragms, due to fatigue

4 Failure function C4: Water ingress to deck due to failed surfacing joint for waterproofing

5 Failure function C14: Cracking at girder restraint at column bearings, due to fatigue.

It can be noted that, despite the list of failure causes being different, there is some commonality between the results of the dual level FMECA's. System level 1 is similar to unit level1. System level 3 links to unit level 4 and 5. System level 4 links to unit level 2 and 3. In fact only the system level, high scoring items which don't pertain to specific physical elements are not reflected in the above list. This does provide evidence that there is a consistency of prioritisation between the two assessments.

The complete unit level FMECA exercise is in Appendix B7. An assessment of the relative merits of the two FMECA's is included in section 5.2.

4.3.3 RCM exercise

The list of recommended types of principal inspection and maintenance regimes per unit of the physical model are listed below. The detailed results are in Appendix B8. The unit numbering system (1st column of the table) is structured as below:

1 Sub structure

2 Superstructure; columns and abutments

3 Superstructure: deck

4 Fittings

5 Services

Table 18 RCM Results

Principal inspection and maintenance regime recommendations arising from RCM study				
Nr	**Unit**	**Principal task per unit**	**Presumed current maintenance regime**	**Difference between RCM Results and current regime**
1.1	Steel friction piles and	Underwater depth survey	bed survey	No

	surround			
1.2	Steel piled cofferdam and river bed material	Diver survey (frequency based on condition) plus condition based repairs	bed survey	No
1.3	Column pier	Condition based inspection frequency with local repairs	As RCM	No
1.4	Abutment foundation	Drainage inspections and condition based cleaning	Any?	Possible
2.1	Column	Condition based inspection frequency, monitoring of cathodic protection, and condition based repairs	As RCM	No
2.2	Main bearings	Condition based inspection frequency and condition based replacement	As RCM	No
2.3	Abutment structure	Condition based inspection frequency and condition based repairs	As RCM	No
2.4	Abutment drainage	Condition based inspection frequency and condition based repairs	Any?	Possible
2.5	Pedestrian lift	Maintenance requirements are legally enforceable	As RCM	No
2.6	Columns in north viaduct	Condition based inspection frequency with local repairs	As RCM	No
3.1	Box girders	Condition based inspection frequency with local repairs	As RCM	No
3.2	Composite slab deck	Condition based inspection frequency and repair	As RCM	No

3.3	Deck upstands	Condition based inspection frequency and local repairs	As RCM	No
3.4	Girder diaphragms	Condition based inspection frequency with local repairs	As RCM	No
3.5	Main deck expansion joint	Condition based inspection frequency with local repairs	As RCM	No
3.6	North viaduct expansion joint	Condition based inspection frequency with local repairs	As RCM	No
3.7	Carriageway surfacing	Time based viewing with local repairs	As RCM	No
3.8	Footpath slab	Condition based inspection frequency and repair	As RCM	No
3.9	Kerb	Condition based viewing frequency and repair	As RCM	No
3.10	Kerb backing	Condition based inspection frequency and repair	As RCM	No
3.11	Services tray	Condition based inspection frequency with local repairs	As RCM	No
3.12	White lining	Condition based inspection frequency and repair	As RCM	No
3.13	Box girder man accesses	Condition based maintenance	As RCM	No
3.14	Paintwork to steel	Condition based inspection frequency and repair	As RCM	No
3.15	Girder fixings at bearings	Condition based inspection frequency and repair	As RCM	No
3.16	Diaphragm fixings	Condition based inspection frequency and repair	As RCM	No
4.1	Cathodic protection	Routine monitoring with condition based repair/replacement	As RCM	No

		i.e. upon occurrence of failure mode		
4.2	Pier anti-collision protection	Condition based inspection frequency and repair	As RCM	No
4.3	Footpath handrails	Condition based inspection frequency and repair	As RCM	No
4.4	Fixings for above	Condition based inspection frequency and repair	As RCM	No
4.5	Parapet handrails	Condition based inspection frequency and repair	As RCM	No
4.6	Fixings for above	Condition based inspection frequency and repair	As RCM	No
4.7	Traffic signs (conventional)	Condition based inspection frequency and repair	As RCM	No
4.8	Variable message traffic signs	Condition based inspection frequency and repair	As RCM	No
4.9	Traffic sign fixings	Condition based inspection frequency and repair	As RCM	No
4.10	Maintenance gantry-stationary state	Time based inspection and reactive maintenance	legal/regulatory requirements	Possible
4.11	Maintenance gantry-mobile state	Time based inspection and reactive maintenance	legal/regulatory requirements	Possible
4.12	Maintenance gantry - vertical access	Time based inspection and reactive maintenance	legal/regulatory requirements	Possible
4.13	Maintenance gantry - motor	Time based inspection and reactive maintenance	legal/regulatory requirements	Possible
5.1	Telecom cable	Time based inspection with condition based replacement	As RCM	No

5.2	Gully	Condition based inspection frequency and repair	As RCM	No
5.3	Drainpipe from gully	Condition based inspection and repair	As RCM	No
5.4	Communications system	Time based replacement	As RCM	No
5.5	Fixings for above	Condition based inspection frequency and repair	As RCM	No
5.6	Weather station	Time based viewing with reactive maintenance	As RCM	No
5.7	Fixings for above	Condition based inspection frequency and repair	As RCM	No
5.8	Light bulbs	Condition based viewing with reactive maintenance	As RCM	No
5.9	Lighting distribution box	Time based viewing with reactive maintenance	As RCM	No
5.10	Lighting column	Condition based inspection frequency and repair	As RCM	No
5.11	Fixings for above	Condition based inspection frequency and repair	As RCM	No
5.12	Lighting cable	Time based inspection with condition based replacement	As RCM	No

The above comparison of maintenance arrangements is still to be subject to verification by bridge operational staff as their major maintenance works are based on the opportunity to share access and inspection arrangements with contractors carrying out improvement and replacement works. The and "no difference" results are therefore based on comparing the RCM recommendations with guidance in the bridge national inspection and maintenance standards. The “possible differences” results reflect the lack of available documented maintenance procedures for these parts so no definitive conclusions could be drawn. The national standards already incorporate much of the philosophy of the RCM exercise so it is probably unsurprising that results are closely comparable. It is also pertinent to note that the RCM exercise usually assigns more than one regime to each unit, dependent upon the context, location and the consequences. Refer to Appendix B8 in this respect for the full list of failure modes. Only the dominant one for each unit is listed above.

The frequency of inspection should bear relationship to the cost, consequences of failure, unit age and condition, and the anticipated timespan between onset of the failure mode and functional failure. In most civil engineering unit cases, where age related environmental degradation mechanisms are at work, a reduced frequency at early life would be justified.

4.3.4 Proposal for retrospective increase in bridge resilience

Analysis of the causes of availability restrictions to bridge users shows that high wind speeds are a major cause of downtime. Resilience and availability would therefore be increased if user protection against high wind forces was improved.

Details of the wind shields for the 2nd Severn Crossing, plus the findings of Kwon et al (2011), were used to sketch a type detail of wind shielding with the objective of reducing wind speeds by 50%. General wind speeds of 90 miles per hour would therefore be reduced to 45. The assumption was made that periods of restricted traffic use would be negligible under this regime. A budget cost for supply and installation was sourced from Holgate Infrastructure (Appendix B9) and this was estimated at £500 per linear metre of windshield, assuming the use of the maintenance gantry and no other operational costs being included. 4600 metres of windshield equates to £2.3 million. If an allowance for access and operational input is added, a cost range of £3.5 to £5 million pounds has been taken.

Paraskevopoulos (2013) has shown a year on year trend of increasing restrictions due to high winds, albeit with a pause in recent years. The average annual increase in periods of the higher wind speeds (70 miles per hour and above) appears to be more marked. Payback periods for initial investments of a/ £3.5 million and b/ £5 million have been calculated for i/ a continuing trend of increasing periods of traffic restrictions and ii/ no ongoing annual increase.

The results are summarised in the table below.

Table 19 Payback Periods

	Increasing trend of wind speeds	No increasing trend
£3.5 million capital cost	3 – 4year payback period	5 – 6year payback period
£5 million capital cost	4 – 5year payback period	8 – 9year payback period

The payback period varies slightly depending on the discount rate used but the exercise demonstrates that, subject to the ability of the bridge to take the extra dead and wind load, the retrospective installation of wind shielding is worthy of serious consideration.

5 Conclusions

5.1 Stages 1 and 2

OBJECTIVE 1/ To review asset management plans for different infrastructure sectors in order to understand a/ the extent to which risk based asset management is implemented and b/ to explore any difference in the maturity of asset management planning across different sectors. If differences are identified a secondary objective is to explore the reasons why.

RESPONSE;

The 'sweep' of asset management progress across the energy, transport, water and communications sectors suggest that gas and electric, water then transport is the order of 'distance travelled', with transport bringing up the rear. Communications are likely to be between water and transport, certainly in terms of business visibility. This then feeds into stage 2 where most of the 'learning transfer' is envisaged to be from water to roads. These statements must be qualified due to gaps in data for the review. These gaps include: no access to internal workings of companies, little personal contact with practitioners, no open access to analytical tools in use.

The extent of adoption of asset management progress in each sector appears dependent on the industry organisational model and the resultant commercial or political imperatives, expressed for example through the drive and authority of the regulator. There may also be a differentiator in terms of the ease of application of life cycle analysis tools, for example industries dependent upon electrical and mechanical fittings rather than long lived civil assets are perceived as having more accurately forecast design lives and therefore more reliable forecast costs. This is likely to be a factor in the early application of asset management practices to these sectors. An alternative way of expressing this is to high light the lack of historic detailed records on service interruptions and maintenance downtime in some civil engineering sectors. A good example of regulatory effectiveness arises from a comparison of the roads and water sectors where the regulator driven focus on asset management has driven the water companies well ahead. The PAS55 assessment sheets in appendix A2 give an overall picture where AMPs have been publicly available.

Appendix A1 includes spread sheets summarising utility sector structure and contacts; essentially acting as references to this section.

In conclusion; in order to drive the widespread use of asset management tools throughout infrastructure sectors, better record keeping and increased emphasis on reducing life cycle costs are required.

5.2 Stage 3

OBJECTIVE 2/ To determine whether the application of integrated logistics support (ILS) to infrastructure projects offers a practical tool within the risk based approach recommended in PAS 55.

RESPONSE

These are ‘bottom up’ analytical tools and therefore depend, initially at least, on experienced and detailed knowledge of the asset under consideration. This needs to be supplemented by availability and maintenance records which are sufficiently detailed to be able to identify service and functional limits and the impact of environmental and loading factors on these. Many civil engineering assets will be found wanting in this regard and the application of these tools will be consequently restricted. An increasing awareness of the value of an asset management approach will encourage asset managers to tackle this shortcoming but adoption will only build if results are found to be valuable.

The dual FMECA results from this exercise on the Tay Road Bridge need to be tested in practice over a period of time but the similarities of the two results; and the verification by means of reviews with the bridge board operations team, lend some confidence that the results would be both repeatable (other engineers attempting the same exercise with the same asset would reach similar conclusions) and reproducible to other civil engineering assets.

This is not to say that further experience of applying the FMECA tool to this asset would not lead to development of the model and a re-ordering of priority risks: it may well do as bridge improvements are made and the impact of further failure causes are experienced. There is also the real consequence of aging of the bridge which will re-prioritise risks.

An example of a high scoring, system level FMECA failure cause (traffic restrictions due to high wind speeds) has been worked through to demonstrate the financial viability of specific resilience improvement proposals. This needs to be tested in engineering terms (i.e. can the bridge deck take the extra dead load) but goes some way to demonstrating possible practical outcomes from this risk exercise.

The RCM exercise has yet to demonstrate value arising from this application. There are at least 2 main reasons for this a/ bridge inspection codes are already based on detailed research on failure modes, causes and deterioration timelines (hence the RCM results in table 17 do not diverge much from current practice) and b/ because of the costs of providing access, and the wider costs of restricting bridge availability, much of the major maintenance works is opportunity based i.e. when major maintenance/replacements are needed, the opportunity is taken to undertake necessary maintenance works too. Existing bridge inspection regimes of general inspections every two years, followed by detailed inspections every 6 years, is proven (through the low instances of bridge failures) to be able to meet public expectations of bridge functionality and reliability.

OBJECTIVE 3/ To compare the results of an FMECA analysis at a system and unit level of detail for the risk based assessment. To assess what level of detail is required for the structural breakdown system in order to allow an effective yet robust FMECA analysis to be carried out.

RESPONSE

Why 2 levels of FMECA assessment? Because resilience is primarily concerned with avoiding or mitigating vulnerabilities arising from threats, the main danger arising to the functionality of assets is if an assessment misses or misjudges the impact of a possible threat or vulnerability. If only one of the two types of 'flow' across the structure, traffic and loading, is assessed, there is a likelihood of missing an important issue. There is little value in improving the ability of the bridge to maintain service levels in the face of external threats if unit reliability is failing to meet an acceptable standard. This is borne out by the different (although similar) priority score issues arising from the two assessments. The resilience of a structure cannot be directly linked to an average score of vulnerability to threats; it only needs one significant threat in one area of vulnerability to cause a significant impact. The choice of level of FMECA study does not appear to be an either/or. The dual approach also neatly links the intrinsic structure with its community value as a mode of traffic conveyance i.e. an asset in terms of its utility. However, it would be appropriate to start both levels with major risks then update and enhance regularly with periodic reviews. These reviews would need to include assessment of new threats as well as reconsideration of existing ones.

The high scoring issues from both FMECA levels are linked but not completely interlinked. Failure to meet service level standards can be independent of minor structural failure. While it is tempting to propose that a system level FMECA be undertaken for the whole structure and a follow on detailed study be done for only selected units or elements, this does not seem to satisfactorily assess all the main risks, because the system level study does not comprehensively draw attention to vulnerabilities which may be exposed by the unit level study. There are a number of similarities in the 2 sets of findings for the Tay Road Bridge but this may not be repeated for other assets.

Would a more detailed FMECA at parts level be useful? This is likely to be related to the scale of the asset; to drop into a more detailed look at parts of mechanical and electrical assemblies would arguably only be justified if particular failure causes required this. If smaller scale assets were being assessed this could be worthwhile.

It proved difficult to see how an RCM exercise would work with the system level FMECA therefore this was based on the unit level FMECA only. One of the benefits of undertaking the RCM exercise was a fuller understanding of the series of steps which constituted the failure mechanisms involved; of which the failure mode was but one stage, albeit an important one. Identification of failure mechanisms; not just modes, was needed in order to correctly identify the appropriate maintenance task. In this way the RCM exercise leads to a fuller understanding of failure modes and hence the accuracy of the FMECA exercise.

OBJECTIVE 4/ To determine whether ILS can be applied efficiently to an assessment of the resilience of infrastructure assets.

RESPONSE

The answer will be critical in driving the dissemination of ILS techniques in infrastructure management sectors. The results arising from one application should not be expected to prove this one way or another and the best lessons arising can only point to some relevant factors:

1. Results of a detailed analysis of the 13 years of bridge availability data have been used to inform some of the system level FMECA ratings and also used in the cost benefit exercise concerning the wind shielding. Were these data to be unavailable then the FMECA results would be more uncertain. The availability of good data and knowledgeable practitioners is therefore important.
2. The lack of new recommendations arising from the RCM exercise in this case should not be equated to a general lack of value from this approach. Application to a different asset may well prove fruitful, particularly as maintenance costs usually dwarf construction costs over the lifetime of an asset.
3. While the staff time involved in constructing the ILS tools is significant; for an asset with a long design life, both FMECA and RCM can prove their value as follows:

When the physical environment changes, the ILS worksheets can quickly be updated to reflect these. New priority risks and vulnerabilities can be highlighted, which focusses maintenance resources in the most effective ways. This is particularly pertinent with the threat of climate change, and in this instance the forecast increase in periods of high wind speeds.

The process of working through an ILS study can highlight gaps in records and blind spots in design awareness of vulnerabilities. This type of study can also provide a structure to address business risks, prioritise their threat levels, and provide a reasoned justification to make a financial case for resources to be spent in a particular area. If this structured, rigorous approach aids understanding of critical parts, it may encourage further application of remote monitoring techniques. The high scoring accorded to 'invisible failure modes' within the FMECA worksheet is particularly suited to driving this.

4/ To sum up; the efficiency of this exercise should be measured over the life cycle of the engineering asset, not as a one-off exercise.

5.3 Suggestions for further research

1) Can this approach work across infrastructure sectors? The models, principles and philosophy applied to the Tay Road Bridge could be tested for their general applicability by using them in a different civil engineering sector; water treatment works or distribution networks could be used.

2) Common lessons arising from a comparison of the two could then be brought out and used to form generic guidance for future applications. The aim would be to arrive at a resilience model which would be capable of widespread application to civil engineering assets, networks or systems.

3) Further development of the resilience model is necessary in order to arrive at a dimensionless quantification of resilience readiness; so that asset and system relative vulnerability can be compared as a management aid when deciding resource allocations.

4) Further application of the RCM exercise to another infrastructure type is necessary in order to measure value.

5) Can value be proven over time? A period of exposing both FMECA and RCM recommendations to real life management and maintenance decision making would ideally feed back into the results and improve these.

References

1. Adaptation sub-committee progress report (2011) ***How well is Scotland preparing for climate change?*** November 2011
2. AEA (2010) ***Adapting the ICT Sector to the impacts of Climate Change – Final report.*** AEA/ED49926/Issue 5.
3. Al-Hajj, A., Al-Saadi, K., ***Shell Group's Asset Management and Implementation*** Saudi Aramco Journal of Technology, Summer 2002
4. Allenby B., Fink J., ***Toward inherently secure and resilient societies.*** Science 309(5737): 1034-1036.
5. Anderson R. T., Neri L. (1990) ***Reliability – Centered Maintenance: Management and Engineering Methods***. Elsevier Applied Science, New York
6. Andrawus J. A., (2008) ***Maintenance optimisation for wind turbines***. PhD thesis, School of Engineering, the Robert Gordon University, Aberdeen
7. Ang A.H.S. ***Life-cycle considerations in risk-informed decisions for design of civil infrastructures.*** Life-cycle civil engineering, page 3-9 2008
8. Atkins, (2011) ***Rail Value for Money Study: Asset Management and Supply Chain Management Assessment of GB Rail Issue 1.1.*** Office of Rail Regulation and Network Rail, May 2011.
9. Attoh-Okine N. O., Cooper A. T., Mensah S. A. (2009) ***Formulation of Resilience Index of Urban Infrastructure Using Belief Functions.*** IEEE Systems Journal, volume 3, No 2, pages 147-153, June 2009.
10. **1**Blanchard B. S., Fabrycky W. J. (1990) ***Systems engineering and analysis.*** (2nd edition), Prentice Hall, New Jersey
11. Borthwick A. (1966) ***The Tay Road Bridge***. Outram & Co, Perth
12. Boussabaine H.A., Kirkham R. J. (2004) ***Whole Life-cycle Costing: Risk and Risk responses.*** Blackwell Publishing Oxford.
13. British Waterways Board. ***British Waterways Corporate Plan for England and Wales 2011/12*** November 2011
14. BSI (2006) ***BS 25999 Business Continuity.*** British Standards Institution
15. BSI (2008) ***BS PAS 55-1 Asset Management.*** British Standards Institution
16. BSI (2008) ***PD 156865 Standardised Method of Life Cycle Costing for Construction Procurement: a supplement to BS ISO 15686-5 Buildings and Constructed Assets – Service Life Planning – part 5: Life Cycle Costing*** British Standards Institution/The International Organisation for Standardisation
17. CBI (2011) ***Building strong foundations. Financing UK infrastructure.*** Confederation of British Industry, London.
18. CIPFA (2010) ***Code of Practice on Transport Infrastructure Assets: Guidance to Support Asset Management, Financial Management and Reporting***. London

19. Civil Contingencies Secretariat, UK Cabinet Office (2010) ***National Risk Register of Civil Emergencies 2010 edition.*** Cabinet Office.

20. Collins B., (2011) ***Transport Services and Systems, Resilience and Investment.*** Department of Transport website, dated 8 January 2011 and published 14 March 2011.

21. Council for Science and Technology (2009) ***A National Infrastructure for the 21st Century***, CST, London

22. County Surveyors Society. ***Framework for Highway Asset Management*** Stationery Office 2004

23. Dawley S., Pike A., Tomaney J., (2010) ***Towards the resilient region?: Policy activism and peripheral region development.*** SERC discussion paper 53.

24. Deadman C., ***Strategic Asset management; The Quest for utility Excellence.*** Troubadour Publishing, Leicester 2010.

25. Department of Defense, USA (1980) ***Military Standard 1629: Procedures for performing a failure mode, effects and criticality analysis.*** The Department of Defense, Washington

26. Draft ISO 55000, ***Asset Management – Overview, principles and terminology.*** Asset Management Council

27. El – Haram M. A., Horner R.M.W. (2002) ***Practical Application of RCM to Local Authority Housing: A Pilot Study.*** Journal of Quality in Maintenance Engineering, MCB University Press, 8 (2) pp135-143

28. El – Haram M. A., Horner R.M.W. (2003) ***Application of the principles of ILS to the development of cost effective maintenance strategies for existing building stock.*** Construction Management and Economics, Vol. 21, 283-296

29. Ferguson N., (2011) ***Civilisation: The West and the Rest.*** Allen Lane,

30. Foster C. L., Monkman D. C. (2000) ***Telecom New Zealand Future Power foundations – Through Risk Control & Asset Management.***

31. Frangopol D.M., Liu M., ***Maintenance and management of civil infrastructure based on condition, safety, optimisation, and life-cycle cost.*** Structure and Infrastructure Engineering 3(1), page 29-41 2007

32. Frangopol, D. M. and Furuta, H., ***Life-cycle cost analysis and design of civil infrastructure systems*** Published papers from a US-Japan workshop on life-cycle cost analysis and design of civil infrastructure systems 2000. American Society of Civil Engineers 2001.

33. Glaister S., Smith J.W., (2009) ***Roads: a utility in need of a strategy.*** Oxford Review of Economic Policy, Volume 25, Number 3, pp.368-390.

34. Hezoucky, F. ***Application of Reliability Centred Maintenance to Optimise Operation and Maintenance in Nuclear Power Plants*** IAEA-TECDOC-1590 International Atomic Energy Agency May 2007

35. HM Government (2010) ***Low Carbon Construction Innovation and Growth Team Final report.*** Department for Business, Innovation and Skills, London

36. HM Government. ***2050 Pathways Analysis*** Department of Energy and Climate Change July 2010

37. HM Government. ***Government Construction Strategy*** Cabinet Office May 2011
38. HM Treasury (2014) ***Infrastructure Cost Review: Measuring and improving delivery.*** HM Treasury, London. July 2014.
39. HM Treasury and Infrastructure UK (2010) ***Infrastructure Cost Review: Main Report.*** HM Treasury, London. December 2010.
40. HM Treasury and Infrastructure UK (2010) ***National Infrastructure Plan 2010***, IUK, London
41. HM Treasury and Infrastructure UK (2011) ***Infrastructure Cost review: Implementation Plan***, IUK, London March 2011
42. Hollnagel E., Woods D.D., Leveson N (2006) ***Resilience Engineering: concepts and precepts.*** Ashgate publishing company, Surrey
43. Hooper R., Armitage R., Gallagher K. A. and Osorio T. (2009) ***Whole-life infrastructure asset management: good practice guide for civil infrastructure,*** CIRIA report C677, London
44. ***Infrastructure Ownership and Control Stock-take: Final report – main findings OFT1290*** Office of Fair Trading December 2010
45. Institute of Asset Management (2011), ***Asset Management – an anatomy Version 1.*** IAM December 2011
46. International Atomic Energy Agency, (2008) ***Application of reliability centred maintenance to optimise operation and maintenance in nuclear power plants.*** International Atomic Energy Agency IAEA-TECDOC-1590, Austria, May 2008.
47. Jones J. (2006) ***Integrated Logistics Support Handbook.*** McGraw-Hill Mexico.
48. ***Keeping the country running: Natural Hazards and Infrastructure. For consultation: A guide to improving the resilience of critical infrastructure and essential services***. Cabinet Office London March 2011
49. Kirwan A., Newby A., (2011) ***Staying on the right track.*** Assets March 2011. Komari I. E. et al (2009) ***Extended dependability analysis of information and control systems by FME(C)A-technique: Models, procedures, application. 2009.*** Fourth international conference on dependability of computer systems 2009
50. Kumar U.D., Crocker J., Knezevic J., El-Haram M. (2000), ***Reliability, Maintenance and Logistic Support. A Life Cycle Approach***. Kluwer Boston
51. Knezevic, J.,(1993), '***Reliability, Maintainability and Supportability – a Probabilistic Approach,'*** McGraw-Hill Book Company, London
52. Knezevic J., (1997), ***Systems Maintainability; Analysis, Engineering and Management,*** Chapman & Hall, London
53. Kwon S.D., Dong H.K., Lee H.L., Ho S.S., (2011) ***Design Criteria of Wind Barriers for Traffic. Part 1: Wind Barrier Performance***. Wind and Structures, Vol 14, No. 1 (2011) pp55-70.
54. Lloyd C., (2002) ***Asset management; whole life management of physical assets.*** Thomas Telford Limited 2010
55. Marenjak S. (2004) ***A generic approach to minimising whole life costs in the building industry***. PhD thesis, Department of Civil Engineering, the University of Dundee

56. Marquez F. P. G., Weston P., Roberts C. ***Failure analysis and diagnostics for railway trackside equipment.*** Engineering Failure Analysis 14, page 1411-1426, 2007

57. McNicoll S. (2008) ***Framework for a standard method of measurement for whole life costing***. MSc dissertation, Department of Civil Engineering, the University of Dundee

58. Moores, AJ. and Rees, JG. (eds.) (2011). ***UK Flood and Coastal Erosion Risk Management Research Strategy. Living with Environmental Change***

59. Moubray J (1997) ***Reliability-centred Maintenance.*** Butterworth-Heinemann Oxford.

60. National Infrastructure Advisory Council (2009) ***Critical Infrastructure Resilience Final Report and Recommendations.*** USA NIAC New York, March 2011

61. NZ National Asset Management Steering Group (NAMS) and the Institute of Public Works Engineering of Australia (2002) ***International Infrastructure Management Manual, United Kingdom edition 2002***, NAMS and IPWEA, Wellington, New Zealand.

62. Ove Arup and Partners (2011). ***Part A Reporter Mandate AO/007: Review Asset Policy, Stewardship and Management of Structures. Final report – review and Benchmarking*** Office of Rail Regulation and Network Rail, March 2011, Leeds

63. Paraskevopoulos, M. (2013), ***Analysis of the Tay Road Bridge Closures: Causes, Costs and Suggestions.***, MSc Dissertation. University of Dundee

64. Planit Valley Project, http://living-planit.com/default.htm

65. Quigley J., Bedford T., Walls L., (2006) ***Estimating rate of occurrence of rare events with empirical bayes: a railway application.*** Reliability Engineering and System Safety 92 (2007) 619-627.

66. Reynolds M. G., (1998) ***Use of information on railway infrastructure condition.*** Proc. Institution of Civil Engineers Trans., 129, May, 80-84.

67. Ridley G. (2011) ***National Security as a Corporate Social Responsibility: Critical Infrastructure Resilience.*** Journal of Business Ethics, volume 103, pages 111-125.

68. Rinaldi S. M., Peerenboom J. P., Kelly T. K. (2001) ***Identifying, Understanding, and Analysing Critical Infrastructure Interdependencies.*** IEEE Control Systems Magazine, pages 11-25. December 2001.

69. Rosenkrantz D J., Goel S., Ravi S. S., Gangolly J. (2009) ***Resilience Metrics for Service-Oriented Networks: A Service Allocation Approach*** IEEE Transactions on Services Computing, Volume 2, No 3, July-September 2009.

70. Science and Engineering of Natural Systems Group at the University of Southampton's School of Electronics and Computer Science (2010 and on-going) ***Resilient Futures 3 year research programme.*** Southampton.

71. Scottish Screen Archives ref nr 2243 - ***Tay Road Bridge*** Campbell Harper Films 1967

72. Scottish Government CNI Group, (2011) ***Secure and Resilient. A strategic framework for critical national infrastructure in Scotland*** Scottish Government.

73. Smith P., Hutchison D., Sterbenz J.P.G., Scholler M., Fessi A., Karaliopoulos M., Lac C., Plattner B. (2011) ***Network Resilience: A Systematic Approach.*** IEEE Communications Magazine, pages 88-97. July 2011

74. Stratford M. A., Stevens T., Hamilton M., Dray A. (2010) ***Strategic asset management modelling of infrastructure assets***. Proceedings of the Institution of Civil Engineers, Engineering and Computational Mechanics June 2010 London

75. Taleb N.M. (2008), ***The Black Swan. The impact of the highly improbable.*** Penguin New York

76. The Cabinet Office (2010) ***Interim Guidance to the Economic Regulated Sectors – Water, Energy, Transport and Communication.*** The Cabinet Office, London

77. ***The Institute of Asset Management website.***

78. The Pitt Review (2008) ***Learning lessons from the 2007 Floods*** The Stationery Office, London.

79. The Royal Institute of International Affairs, N***avigating Uncharted Waters, Constructive Approaches to Complexity, The 1997 Chatham House Forum Report,*** London 1997

80. The Royal Institute of International Affairs, ***Unsettled Times, Three Stony paths to 2015, The 1996 Chatham House Forum Report,*** London 1996

81. thisbigcity.net/the-bionic-city-a-natural-blueprint-for-future-cities/

82. Thomson A. (2011) ***The Salvo Project: Innovative approaches to decision-making for the management of aging physical assets.*** Infra assets, Kuala Lumpur February 2011. The Woodhouse Partnership Ltd

83. Transport Scotland, (2011) ***The Performance Audit Group's Annual Report 2010/11*** Pagplus/Halcrow

84. ***UK Infrastructure Transitions Research Consortium. An interdisciplinary research programme on long term dynamics of interdependent infrastructure systems.*** Tyndall Centre for Climate Change Research and the UK Energy Research Centre.

85. UK Water Industry Research Limited (2013**)** ***Report ref No. 13/RG/06/2 Resilience planning: Good Practice Guide – Summary Report***. UKWIR, London.

86. ***Urban Futures research project 2008-2012***. www.urban-futures.org

87. US Department of Defense (1983) ***Military Standard 1388*-1A, Logistic Support Analysis,** USA

88. Utne I. B., Hokstad P., Vatn J., (2011) ***A method for risk modelling of interdependencies in critical infrastructures.*** Reliability Engineering and System Safety 96 (2011) 671-678.

89. Vugrin E. D., Warren D. E., Ehlen M. A. (2011) ***A Resilience Assessment Framework for Infrastructure and Economic Systems: Quantitative and Qualitative Resilience Analysis of Petrochemical Supply Chains to a Hurricane.*** Process Safety Progress, volume 30, No 3, pages 280-290, September 2011.

90. Willingham M. (2008) ***Focusing on Regional Resilience.*** Proceedings of the IEEE, volume 96, No 5, pages 755-757. May 2008.

91. Woodhouse J. (2001) ***Combining the best bits of RCM, RBI, TPM, TQM, Six-sigma and other 'solutions',*** Institute of Asset Management website

Bibliography

1. Adaptation sub-committee progress report (2011) ***Adapting to climate change in the UK: Measuring Progress.***

2. Anglian Water (2009) ***PR09 Final Business Plan*** Anglian Water website.

3. ***AS/NZS 4536:1999 'Life cycle costing - An application guide'.***

4. Asif A. (1988) ***Simple generic models for cost-significant estimating of construction project costs***. (excluding chapters 1, 2, 6 and 7) PhD thesis, Department of Civil Engineering, the University of Dundee

5. Atkins, (2008) ***Advice on the prioritisation of smaller transport schemes.*** Department of Transport.

6. Attoh-Okine N., Mensah S. A., ***Sensor Fusion and Civil Infrastructure Systems Monitoring: A Valuation Algebras Analysis of Output Data*** IEEE sensors journal, vol 9, no 11, November 2009

7. Audit Scotland (2011) ***Maintaining Scotland's roads: A follow-up report.*** Edinburgh.

8. Blockley D., Agarwal J., Godfrey P. (2012), ***Infrastructure resilience for high-impact low-chance risks***. Institution of Civil Engineers proceedings vol 165 issue CE6 November 2012

9. ***Bridge Condition Indicators. Volumes 1, 2 and 3. Commission report, Guidance Notes***. County Surveyors Society July 2002.

10. BS EN 1990:2002 ***Basis of structural design***. British Standards Institution/The International Organisation for Standardisation

11. British Construction Information Service. ***Whole Life Costing Spread sheet – Standardised method of life cycle costing for construction Procurement***

12. British Infrastructure Commission report (2011), ***Tackling the Infrastructure Puzzle***, British Chambers of Commerce, London

13. BSI and Constructing Excellence (2008) ***Rethinking standards in Construction. Developing the next generation of construction standards.*** Workshop Report.

14. Buldyrev S. V.Parshani R., Paul G., Stanley H.E., Havlin S. (2010) ***Catastrophic cascade of failures in interdependent networks.*** Nature **464**, 1025-1028 (15 April 2010).

15. Carnero M. C., ***An evaluation system of the setting up of predictive maintenance programmes.*** Reliability Engineering and System Safety 91, page 945-963 2006

16. Constructing Excellence and Pinsent Masons LLP. ***Infrastructure in the New Era.*** June 2011

17. ***Constructing Excellence Website*** Local Government Task Force

18. ***Construction Best Practice Programme*** Department of Environment, Transport and Regions and the Construction Industry Board

19. Construction Skills Council. ***Construction Skills Strategic Plan 2011-2015,*** 2011

20. Crisp J. J. (2003) ***Asset management in Electricity Transmission Utilities: Investigation into Factors Affecting and their Impact on the Network.*** PhD thesis, School of Electrical and Electronic Engineering, Queensland University of Technology, Brisbane, Australia, August 2003.

21. Dailey K.W. (2004) ***The FMEA pocket handbook.*** DW Publishing USA.

22. Davison R. W. ***Maintenance at Chapelcross.*** Power Station Maintenance: Profitability Through Reliability, 30 March - 1 April 1998.Conference Publication **No.** 452, *0* IEE

23. DEFRA, 2012, ***UK Climate Change Risk Assessment: Government Report.*** The Stationery Office, London, January 2012.

24. Department of Health Finance, Performance and Operations Directorate (2008) ***Treasury's Value for Money Assessment for PFI – Guidance for NHS build schemes.*** The Stationery Office, London.

25. Department of Transport, (2000) ***Manual of Contract Documents for Highway Works.*** Stationery Office, London.

26. Ding Y., Zuo M. J., Tian Z., Li W. ***The Hierarchical Weighted Multi-State k-out-of-n System Model and its Application for Infrastructure Management.*** IEEE Transactions on Reliability, Vol 59, No 3, September 2010

27. E.C. Harris. ***International Construction Cost Comparison Report*** August 2011

28. Egan, J. Strategic Forum for Construction (2002) ***Accelerating Change***, Strategic Forum for Construction, London

29. El – Haram M. A., Horner R.M.W. (1998) ***Factors affecting Life Cycle Cost in the Construction Industry.*** 8 International Symposium MIRCE, University of Exeter, Exeter.

30. El – Haram M. A., Horner R.M.W. (2006) ***Application of FMECA to smart air brick - Unpublished draft for discussion with BBA*** Whole Life Consultants Ltd, the University of Dundee

31. El – Haram M. A., Horner R.M.W., Munns A. K. (1997) ***Building Maintenance Strategy: a new management approach.*** Journal of Quality in Maintenance Engineering, MCB University Press, 3 (4) pp273-281

32. El-Haram M. A. (1995) ***Integrated approach to condition based reliability assessment and maintenance planning***. PhD thesis, Faculty of Engineering, the University of Exeter

33. Faber M. H., Stewart M. G., ***Risk assessment for civil engineering facilities: critical overview and discussion.*** Reliability Engineering and System Safety 80, page 173-184 2003

34. Farmani R., Walters G. A., Savic D. A., ***Trade-off between Total Cost and reliability for Anytown Water Distribution Network.*** Journal of Water Resource Planning and Management. Volume 131, Issue 3, pp 161-171. May/June 2005.

35. Farmani R., Walters G., Savic D., (2006) ***Evolutionary multi-objective optimization of the design and operation of water distribution network: total cost vs. reliability vs. water quality.*** Journal of Hydroinformatics 08.3.

36. Fisher J. W.; Roy, S. (2011) ***Fatigue of steel bridge infrastructure***. Structure and Infrastructure Engineering Vol7, Issue 7-8, July 2011, P 457-475

37. Flanagan R., Norman G., (1983) ***Life cycle costing for construction.*** RICS July 1983 London.

38. Flores-Colen I., De Brito J., ***A systematic approach for maintenance budgeting of buildings facades based on predictive and preventive strategies.*** Construction and Building Materials 24, page 1718-1729 2010

39. Frangopol D. M., ***Life-cycle cost design of deteriorating structures.*** Journal of structural engineering vol 125 iss2 page 224 1999

40. Furuta H., Frangopol D.M., Saito M., ***Life-cycle cost design of deteriorating bridges using genetic algorithms.*** Structural Engineering in the 21st century, page 243-246, 1999

41. Ghods A., Khaboury D. A., Zakerifar R. (2002) ***Case Study of Distribution Network Reliability Analysis Based on Probabilistic Method.***

42. Gomez F., Althoefer K., Seneviratne L. D., ***Simulation of ultrasound imaging inside fully charged pipes.*** Automation in Construction 15, page 355-364 2005

43. Haider A. (2008) ***Fallacies of technological determinism – lessons for asset management.*** 2008

44. Hameed Z., Ahn S.H., Cho Y.M., ***Practical aspects of a condition monitoring system for a wind turbine with emphasis on its design, system architecture, testing and installation.*** Renewable Energy 35 page 879-894 2010

45. Heisig P., Caldwell N.H.M., Grebici K., Clarkson P.J., ***Exploring knowledge and information needs in engineering from the past and for the future – results from a survey.*** Design Studies Vol 31 No. 5 September 2010

46. Helm D. (2009) ***Infrastructure investment, the cost of capital, and regulation: an assessment.*** Oxford Review of Economic Policy, Volume 25, Number 3, pp.307-326.

47. Hewlett P. C. ***BBA Product Assessment Development using FMEA/FMECA*** [*] ***and Risk Analysis*** Draft Manual

48. Highways Agency **(**2009) ***Network Management Manual Part 2 – Asset Management Records*** Version 1 amendment 8

49. Highways Agency (2011) ***Business Plan 2011-12*** Highways Agency Publications code PR 138/10

50. HM Government. ***Low Carbon Construction Innovation and Growth Team Final Report*** Department for Business, Innovation and Skills November 2010

51. HM Treasury (2010) ***Whole of government accounts. Accounting for Highways Infrastructure Assets in the local authority sector on a depreciated replacement cost basis. Interim accounting arrangements for the period up to 2012-13.*** HM Treasury, London.

52. HM Treasury ***Whole of Government Accounts. Accounting for Highways Infrastructure Assets in the Local Authority Sector on a Depreciated Replacement Cost Basis. Interim Accounting Arrangements for the Period up to 2012-13.*** March 2010

53. HMSO (2003) ***The Green Book – Appraisal and Evaluation in Central Government: treasury guidance.*** HM Treasury, The Stationery Office, London.

54. Hoult N., Bennett P. J., Stoianov I., Fidler P., Maksimovic C., Middleton C., Graham N., Soga K. ***Wireless sensor networks: creating 'smart infrastructure'.*** Proceedings of ICE Civil engineering 162 August 2009 pages 136-143

55. Howard A.J. (2008) ***Applying the lessons learnt in Asset Management around the world to the development of the ample tool.*** WIT transactions on the built environment, Vol 103, pp75-84 2008

56. ICE Scotland (2011) ***The State of the Nation Briefing. Scotland Infrastructure Special 2011.*** Institution of Civil Engineers.

57. Institute of Asset Management, (2008) ***2008 Asset Management Competence Requirements Framework.*** Issue 1.0 November 2008.

58. Institute of Asset Management, (2008) ***Guidance on using the 2008 Asset Management Competence Requirements Framework.*** Issue 1.0 November 2008.

59. Institute of Asset Management, (2009) ***Asset Information Guidelines.*** Web version 1.3 May 2009.

60. Institute of Asset Management, (2009) ***PAM template.*** Web version June 2011

61. Institution of Civil Engineers (2009) ***The State of the Nation: Defending Critical Infrastructure***, ICE, London

62. Institution of Civil Engineers (2010) ***The State of the Nation: Infrastructure 2010***, ICE, London

63. Isles V. and Cranfield S., **(**2004) ***Managing change in the NHS. Developing change management skills. A resource for health care professionals and managers***. NHS Service Delivery and Organisation.

64. ***ISO 15663-1: 'Petroleum and natural gas industries. Life cycle costing. Methodology'***

65. Jiang B., Sample A.P., Mamishev A.V. ***Mobile Monitoring for Distributed Infrastructures.*** Proceedings of the IEEE, International conference on mechatronics and automation, Niagara Falls, Canada July 2005

66. Juho A., Altamirano M., Weijnen M. (2006) ***How to define the condition of an infrastructure for different asset management purposes?*** IEEE international conference on systems, man, and cybernetics October 8-11 2006 Taipei, Taiwan

67. Kara-Zaitri C., Keller A. Z., Barody I., Fleming P. V. (1991) **A*n improved FMEA methodology.*** Proceedings Annual Reliability and Maintainability Symposium 1991

68. Kelly J. R., Hunter K. (2002) ***A standard approach to the whole life costing of small scale, sustainable, energy generation and design solutions***. School of the Built and Natural Environment, Glasgow Caledonian University, Glasgow

69. Koppenjan J. F. M. and Verlaan J.G., (2002) ***Tensions between contracting and asset management: a conceptual framework for comparing public infrastructure sectors.***

70. Korayem M.H., Iravani A., ***Improvement of 3P and 6R mechanical robots reliability and quality applying FMEA and QFD approaches.*** Robotics and Computer-integrated Manufacturing 24, page 472-487, 2008

71. Kumar R., Gardoni P., Sanchez-Silva M. ***Effect of cumulative seismic damage and corrosion on the life-cycle cost of reinforced concrete bridges.*** Earthquake Engineering & Structural Dynamics vol 38 issue 7 17 Nov 2008
72. LaSala K. P., ***Human Performance Reliability: A Historical Perspective*** IEEE Transactions on Reliability, Vol 47, No. 3, September 1998
73. Lee II E. E., Mitchell J. E., Wallace W. A., ***Restoration of Services in Interdependent Infrastructure Systems: A Network Flows Approach.*** IEEE Transactions on Systems, Man and Cybernetics – Part C: Applications and reviews, Vol 37, No 6, November 2007
74. Levery M., ***Outsourcing maintenance – a question of strategy.*** Engineering Management Journal, February 1998
75. Li Z., Madanu S., Zhou B., Wang Y. ***A Heuristic Approach for Selecting Highway Investment Alternatives.*** Computer-Aided Civil and Infrastructure Engineering 25 (2010) 427-439
76. ***Lifecycle.*** Cirp Annals – Manufacturing Technology 59, page 740-759, 2010
77. MacGillivray B. H., Pollard S. J. T., ***What can water utilities do to improve risk management within their business functions? An improved tool and application of process benchmarking.*** Environment International 34, page 1120-1131, 2008
78. Macke M., Higuchi S. ***Optimizing maintenance interventions for deteriorating structures using cost-benefit criteria.*** Journal of structural engineering vol 133 iss7 page 925-934 July 2007
79. ***Maintaining Scotland's Roads; A follow-up report*** Audit Scotland February 2011
80. Male S., Kelly J., Gronqvist M., Graham D. ***Managing value as a management style for projects*** International Journal of Project Management 25 (2007) 107–114 2007
81. Manson S. M. ***Simplifying Complexity: a review of complexity theory*** Geoforum 32 (2001) 405-414
82. Maropoulos P. G., Ceglarek D., ***Design Verification and Validation in Product***
83. McBain W., Wilkes D., Retter M. ***Flood resilience and resistance for critical infrastructure***. Ciria C688 London 2010
84. McDermott R.E., Mikulak R. J., Beauregard M. R. (2009) ***The Basics of FMEA 2nd edition.*** Taylor and Francis group.
85. McGowan P. H. (1994) ***Integrated cost and time models for measuring, valuing and controlling construction projects***. PhD thesis, Department of Civil Engineering, the University of Dundee
86. McLeish J. G., ***Enhancing MIL-HDBK-217 Reliability Predictions with Physics of Failure Methods.*** Advancing Microelectronics vol37, issue2, pp28-32, 2010
87. Mikulecky D. C. ***The emergence of complexity; science coming of age or science growing old?*** Computers and Chemistry 25 (2001) 341–348
88. Moore W. J., Starr A. G., ***An intelligent maintenance system for continuous cost-based prioritisation of maintenance activities.*** Computers in Industry 57, page 595-606, 2006

89. Morimoto R. (2010) ***Estimating the benefits of effectively and proactively maintaining infrastructure with the innovative smart infrastructure sensor system.*** Socio-Economic Planning Sciences 44 (2010) 247-257.

90. Morimoto R. ***Estimating the benefits of effectively and proactively maintaining infrastructure with the innovative Smart Infrastructure sensor system.*** Socio-Economic Planning Sciences 44 (2010) p247-257.

91. National Audit Office Report (2003) ***PFI: Construction Performance***. The Stationery Office, London

92. National Audit Office Report (2007) ***Building for the future: Sustainable construction and refurbishment on the government estate***. The Stationery Office, London

93. Noortwijk J. M., Frangopol D. M., ***Two probabilistic life-cycle maintenance models for deteriorating civil infrastructures.*** Probabilistic Engineering Mechanics Vol 19 page 345-359, 2004.

94. Nuclear Safety Directorate **(**2005) ***Structural Integrity: Civil Engineering Aspects*** Technical Assessment Guide T/AST/017 issue 2

95. Office of Rail Regulation (2010). ***Annual efficiency and finance assessment of Network Rail 2009-10*** Office of Rail Regulation September 2010

96. Ofwat (2009) ***PR09/32 Capital maintenance and asset management assessments (AMA) for draft determinations – technical note and appendices.*** Ofwat.

97. Ofwat (2009) ***PR09/37 The PR09 assessment process for assessing capital maintenance plans.*** Ofwat.

98. Ofwat discussion paper, (2011) ***Input, outputs and outcomes – what should price limits deliver? A discussion paper.*** Ofwat, Birmingham.

99. ***OGC gateway review on website***

100. PAGplus, Halcrow Group limited (2011) ***Report on winter service provided by Bear on M8 between 5 and 6 December 2010.*** Transport Scotland.

101. Papadopoulos Y., Grante C., ***Evolving car designs using model-based automated safety analysis and optimisation techniques.*** The Journal of Systems and Software 76, page 77-89 2005

102. ***PAS 55 Assessment Methodology (PAM).*** Institute of Asset Management website.

103. Pollard S. J. T., Strutt J. E., MacGillivray B. H., Hamilton P. D., Hrudey S. E., ***Risk analysis and management in the water utility sector. A review of drivers, tools and techniques.*** Process Safety and Environmental Protection 82, page 453-462. November 2004

104. Quocirca insight report, (2006) ***Utility Businesses and Asset Management Optimising the use of assets for the benefit of customers and shareholders and to satisfy regulators.*** Quocirca.

105. Richardson K. ***The hegemony of the physical sciences: an exploration in complexity thinking.*** Futures 37 (2005) 615–653

106. Saegrov S., Baptista J. F. M., Conroy P., Herz R. K., LeGauffre P., Moss G., Oddevald J.E., Rajani B., Schiatti M., ***Rehabilitation of water networks. Survey of research needs and on-going efforts.*** Urban Water 1, pp. 15-22, 1999

107. Salgado P. P., Quintana S.C., Pereira A. G., Ituarte D. M., Mateos B. P. (2006) ***Participative multi-criteria analysis for the evaluation of water governance alternatives. A case in the Costa del Sol (Malaga).*** Ecological Economics Vol 68, Issue 4, 15 Feb 2009, 990-1005

108. Saroop S. H., Allopi D., (2007) ***Infrastructure cost planning; a design led approach.*** Proceedings of the Institution of Civil Engineers. Municipal Engineer 160 pages 145-149.

109. Schwab K. ***The Global Competitiveness report 2010-2011***. World Economic Forum Geneva Switzerland 2010

110. Scott M., Rezaizadeh A., Delahaza A., Santos C. G., Moore M., Graybeal B., Washer G., ***A comparison of non-destructive evaluation methods for bridge deck assessment.*** NDT&E International 36 (2003) 245–255

111. ***Scottish Construction Centre*** website and publications

112. Scottish Government consultation paper (2010) ***Building a Hydro Nation – A Consultation.*** The Scottish Government, Edinburgh.

113. Scottish Government, (2005) ***Maintaining Standards – A public report on trunk road maintenance in 2004/5.*** Scottish Government.

114. Scottish Government, (2010 and 2011) ***Scottish Resilience News.***

115. Scottish Water, (2009) ***Strategic Asset Capacity and Development Plan 2009***

116. Scottish Water, (2010) ***Delivery Plan 2010-15*** March 2010

117. Shohet, I. M. and Paciuk, M. (2006) ***Service life prediction of exterior cladding components under failure conditions.*** Construction Management and Economics, Vol. 24, 131-148

118. Smith P.F., (2009) ***Building for a changing climate; The challenge for construction, planning and energy.*** Earthscan London October 2009.

119. South Yorkshire Local Transport Plan Partnership (2010) ***South Yorkshire Highway Asset Management Plan September 2010***.

120. Tay Road Bridge Joint Board (2013) ***Asset Management Plan***. Draft issue of May 2013.

121. Tay Road Bridge Joint Board (2013) ***Asset Management Lifecycle Plan***. September 2013 issue.

122. Tay Road Bridge Joint Board (2010) ***Risk management Strategic Plan and Strategic Risk Register (2010-2012).***

123. The Building (Scotland) Regulations 2004 ***Scottish Building Standards Technical Handbook*** 2010 edition

124. The Risk Consortium, Department of Management Science at the University of Strathclyde.

125. Thomas J., Mengel T. ***Preparing project managers to deal with complexity – Advanced project management education*** International Journal of Project Management 26 (2008) 304–315

126. Transport Scotland, (2007) ***Road Asset Management Plan for Scottish Trunk Roads April 2007-March 2009***

127. Transport Scotland, (2010) ***The Performance Audit Group's Annual Report 2009/10*** Pagplus/Halcrow

128. ***Treasury PFI value for money quantitative assessment model*** (spread sheet)

129. UK Cabinet Office (2011) ***Government Construction Strategy May 2011.*** Cabinet Office.

130. ***UK Flood and Coastal Erosion Risk Management Research Strategy (draft)*** Living with Environmental Change 2011

131. UK MOD (1996) ***Defence Standard 00-60, Issue 1, Integrated Logistic Support,*** UK

132. UK Roads Liaison Group (2005) ***Management of Highway Structures. A Code of Practice.*** The Stationery Office, London.

133. UK Roads Liaison Group (2005) ***Well-maintained Highways. Code of Practice for Highway Maintenance Management.*** The Stationery Office, July 2005, London.

134. UK roads liaison group, (2005) ***Management of Highway Structures.*** Stationery Office, London September 2005.

135. UKWIR (2002) ***Technical Summary extracted from UKWIR report 'Capital Maintenance Planning Common Framework: review of Current Practice'.*** Report ref no. 05/RG/05/14.

136. Van Heck G. J., (2008) ***Asset management frameworks for (drinking water) infrastructures around the world.***

137. Van Leeuwen J. F., Nauta M. J, De Kaste D., Odekerken-Rombouts Y. M. C. F., Oldenhof M. T., Vredenbregt M. J., Barends D. M.., ***Risk analysis by FMEA as an element of analytical validation*** A Journal of Pharmaceutical and Biomedical Analysis 50, pp. 1085-1087, 2009.

138. Walsh C.L., et al, (2007) ***Building Knowledge for a Changing Climate: collaborative research to understand and adapt to the impacts of climate change on infrastructure, the built environment and utilities.*** Newcastle University, March 2007.

139. Wang N. (2005) ***New approaches to optimising whole life costing predictions of building and civil engineering projects***. PhD thesis, Department of Civil Engineering, the University of Dundee

140. Waste and Resources Action Programme (2008) ***Materials resource efficiency in street works. Utility Industry Agreement***

141. Water Industry Commission for Scotland (2010) ***Water Industry commission's response to RSE's enquiry 'Facing up to climate change'.***

142. Water Sector Innovation Leadership Group (2011) ***Innovation Priorities for the Water Sector.*** Ofwat May 2011.

143. Water UK (2008) ***How the Water Industry is adapting to Climate Change.*** Water UK briefing December 2008.

144. Welte T. M. ***Using state diagrams for modelling maintenance of deteriorating systems.*** IEEE transactions on power systems vol 24, no. 1, February 2009

145. WERF ***Assessing utility practices with the strategic asset management gap analysis tool (SAM GAP)*** Werf project nr SAM2R06COa

146. White I, (2010) ***Water and the city: risk, resilience and planning for a sustainable future.*** Routledge Abingdon.

147. ***Whole life Consultants*** website

148. Willems A., Janssen M., Verstegen C., Bedford T. (2005) ***Expert quantification of uncertainties in a risk analysis for an infrastructure project.*** Journal of Risk Research, volume 8, issue 1, pages 3-17.

149. Woodhouse J. ***Value, Risks and Decision-making*** Assets May 2011, The Institute of Asset Management Magazine

150. Zakieh R. (1991) ***Quantity-significance and its application to construction project modelling***. PhD thesis, Department of Civil Engineering, the University of Dundee

Glossary

Absorptive capacity The ability of the system to endure a disruption without significant deviation from normal operating performance (NIAC 2009)

Adaptive capacity The general ability of institutions, systems, and individuals to adjust to potential damage, to take advantage of opportunities, or to cope with the consequences.

ARM Availability, reliability and maintenance analysis. An ILS process to quantify all three.

Asset management (abbreviated to AM) Defined in PAS55 as 'the systematic and coordinated activities and practices through which an organisation optimally and sustainably manages its assets and asset systems, their associated performance, risks and expenditures over their life cycles for the purpose of achieving its organisational strategic plan'.

Asset management plan (abbreviated to AMP) A document specifying activities and resources, responsibilities and timescales for implementing the asset management strategy and delivering the asset management objectives (PAS55 part 1 page 2)

Asset management (purpose of): on a more explanatory basis than above, another definition is attempted (Lloyd page xiii) as: 'Asset management is a strategic discipline which gives rigour and accountability to the way organisations decide:

- How, where and in what to invest

- Which assets are most critical.
- What risks need to be managed
- What demands must be served
- What needs to be known
- How this knowledge should be captured and circulated
- How organisations should be structured and led
- What types and teams of people they need
- How activities should be carried out
- How actual performance should be measured
- That improvements are needed'

Availability

The probability that an item is in a state of functioning at a given point in time (point availability) or over a stated period of time (interval availability) when operated, maintained and supported in a prescribed manner (Kumar et al 2000). This is normally measured as a ratio representing the proportion of the operational time during which the asset and/or system is available for operation.

Bottom-up assessment of resilience - focusses on a systematic analysis of the effects of individual hazard events at critical assets**.** It examines the root elements of the system and how the impact of each hazard could propagate through the system, potentially triggering system failure and possibly loss of service. (UKWIR 2013)

Critical National Infrastructure (CNI)

Those elements of infrastructure, the loss or compromise of which would have a major, detrimental impact on the availability or integrity of essential services, leading to severe economic or social consequences or to loss of life (CPNI website)

Durability

Ability of an item to perform a given function at any given time based on required performance

Failure A loss of function or reduced capability. There are three failure definitions (El-Haram 1995). 1) an element has suddenly become completely inoperable and can no longer perform its required function 2) an element is still operable but incapable of fulfilling some or all of its intended functions at the level of performance originally specified and 3) an element has gradually deteriorated to an unsatisfactory level of performance or condition, and its continued operation is either unsafe, uneconomical or aesthetically unacceptable. Taken together, a functional failure is defined as the inability of any asset to fulfil a function to a standard of performance which is acceptable to the user (Moubray 1997). This leads directly to the report specific definition below.

Failure consequences

Describes what happens when a failure mode occurs; answers the question 'how does it matter?' (Moubray 1997). This can be thought of as the impact of the failure effects.

Failure effects

Describes what happens when a failure mode occurs – answers the question – what happens? (Moubray 1997). This can be thought of as the early physical symptoms following failure.

Failure definition in the RCM process in this report A loss of function or reduced capability sufficient to cause the bridge manager to impose limitations on bridge users (including bridge closure).

Failure mode The way in which an item failure manifests itself to the user. In other words, the first visible physical sign of failure.

FMEA Failure mode, effects and analysis. A systematic approach to identify all the possible ways in which failure of an element, service or piece of equipment can occur, together with its causes, and thus the failure's potential effect on the network or structure's elements, services and equipment.

FMECA

Failure mode, effects and criticality analysis. As above but with the addition of criticality analysis. The objective is to determine the ways in which equipment can fail, and the effects of such failures on other elements of the system. Output data are: List of all possible failure modes, causes and effects of each failure mode, list of critical elements and list of elements which require design improvement – then used as input data for the RCM analysis and for future development of the maintenance strategy.

FTA Fault tree analysis. A top down approach which identifies ways in which a particular system failure can occur and the probability of its occurrence (Kumar et al 2000). It allows quantification of low level failures which cause larger problems.

Hazard An entity with the ability to cause harm.

ILS

Integrated logistic support. A structured management approach aimed at ensuring that assets are designed and maintained to deliver maximum whole life value whilst achieving the required levels of performance and reliability. Availability, reliability, durability, maintainability, supportability and safety are all considered in as much detail as possible, normally by an expert panel. ILS comprises a suite of tools including failure modes, effects and criticality analysis (FMECA); reliability centred maintenance (RCM);

Availability, reliability and maintainability analysis (ARM); level of repair analysis (LORA); fault tree analysis (FTA); logistic support analysis (LSA).

Infrastructure

Nii et al state that infrastructure can be described as “the systems and organisations required for the functioning of a society”. This also allows inclusion of non-stationary water treatment plant process units, for example.

Infrastructure

“a network of independent, mostly privately-owned, man-made systems and processes that function collaboratively and synergistically to produce and distribute a continuous flow of essential goods and services”. Critical Foundations 1997

Infrastructure assets

Stationary systems forming a network and serving whole communities, where the system as a whole is intended to be maintained indefinitely at a particular level of service potential by the continuing replacement and refurbishment of its components. The network may include normally recognised ordinary assets as components. (IIMM 2002).

Infrastructure dependency: A linkage or connection between two infrastructures, through which the state of one infrastructure influences or is correlated to the state of the other. (Rinaldi et al 2001)

Infrastructure interdependency: A bidirectional relationship between two infrastructures through which the state of each infrastructure influences or is correlated to the state of the other. (Rinaldi et al 2001)

Infrastructure resilience consists of 4 elements: resistance, reliability, redundancy, response and recovery (Cabinet Office Natural Hazards and Infrastructure 2011)

Infrastructure spatial scale for analysis (based on Perrow's taxonomy):

Part: smallest component of a system that can be identified in an analysis (e.g. a bolt)

Unit: a functionally related collection of parts (e.g. a bridge bearing)

Subsystem: an array of units (e.g. the bridge deck)

System: a grouping of subsystems (e.g. the complete bridge)

Infrastructure: a complete collection of like systems (e.g. the complete regional road network)

Level of Service

The defined service quality for a particular activity or service area against which service performance may be measured. Service levels usually relate to quality, quantity, reliability, responsiveness, environmental acceptability and cost. (IIMM manual 2002)

Life cycle cost (ISO 15686, part 5) LCC is the "cost of an asset, or its parts throughout its life cycle, while fulfilling the performance requirements"

LORA

Level of repair analysis. A procedure which determines in a systematic way the cost of alternative maintenance options and maintenance levels, taking into account manpower costs, support equipment and spare parts (Blanchard & Fabrycky 1991). i.e. do we repair on site, off site, or discard – the result is to find the maintenance level which minimizes total support cost.

LSA

Logistic support analysis. The process employed on an iterative basis throughout system development that addresses the aspect of supportability in design.

Maintainability A scientific discipline which studies complexity, factors and resources related to the tasks needed to be performed by the user in order to maintain the functionality of a system/product, and works out methods for their quantification, assessment, prediction and improvement (Knezevic 1997). Normally measured in terms of mean time to repair (MTTR), maintenance labour hours per maintenance task (MLH/MT), maintenance labour cost per maintenance task (MLC/MT).

Optimize

achieve by a quantitative or qualitative method, as appropriate, the best value compromise between conflicting factors such as performance, costs, and retained risk within any non-negotiable constraints (PAS55 part 1 page 4)

Perturbation a disturbance of motion, course, arrangement, or state of equilibrium. A small change in a physical system, most often in a physical system at equilibrium that is disturbed from the outside.

Publicly available specification A Publicly Available Specification (PAS) is a sponsored fast-track standard driven by the needs of the client organizations and developed according to guidelines set out by BSI.

Key stakeholders are brought together to collaboratively produce a BSI-endorsed PAS that has all the functionality of a British Standard for the purposes of creating management systems, product benchmarks and codes of practice. After two years the PAS is reviewed and a decision is made as to whether it should be taken forward to become a formal British Standard. (British Standards shop website)

RCM

Reliability centred maintenance. A systematic approach for selecting applicable and effective preventive maintenance tasks for each item in a system, taking into consideration failure consequences. (Moubray 1996) It is a method for directing maintenance efforts to the areas of greatest importance for reliable system operation and arises from a rigorous analysis of the consequences of failure.

Reliability

ISO 60050 (191): the ability of an item to perform a required function under given conditions for a given time interval. Normally measured by mean time between failures (MTBF) or mean time to failure (MTTF).

Reliability engineering

consist of the systematic application of engineering principles and techniques throughout a product lifecycle to ensure that a system or device has the ability to perform a required function under given conditions for a given time interval. (taken from Asset Management – an Anatomy)

Reliability/Resilience contrast

The term ‘reliability’ is applicable only when the item in question is used within the conditions for which it was designed. Resilience is used in this report to include design conditions but also describe behaviour or characteristics under conditions beyond the design limits.

Repeatability

The same exercise repeated by the same people gives the same results.

Reproducibility The same exercise reproduced by different people gives the same results.

Resilience

"Given the occurrence of a particular disruptive event (or set of events), the resilience of a system to that event (or events) is the ability to reduce efficiently both the magnitude and duration of the deviation from targeted system service levels". (adapted from Vugrin et al 2011)

Restorative capacity (Vugrin 2011)

The ability of a system to be repaired easily

Risk The probability that a hazard will cause harm (Health and Safety Executive definition).

Robustness

"The ability of an item or system to maintain its function when subject to changes or perturbations and uncertain conditions". (Blockley et al 2012)

Serviceability

The ability of a system to be serviced easily.

STEEPLE analysis An assessment of positive and negative factors in the macro environment within the categories of social, technological, environmental, economic, political, legal and ethical factors.

Structural system Load bearing elements of a building or civil engineering works and the way in which these elements function together.

Supportability

The inherent characteristics of an item related to its ability to be supported by the required resources for the execution of the specified maintenance task (Knezevic 1993). Required resources must be planned and developed; a main measure is mean time to support (MTTS). An assessment is defined by US department of defence 1983 standard 1388-1A.

Terotechnology

Initiated by the UK Ministry of Industry in 1968. Also known as life-cycle costing.

Theory of significance In any set of data, the greatest amount of information is obtained for the least effort by considering only data whose value is greater than the mean. (essentially a variation on the 80/20 rule).

Top-down assessment of resilience – This approach considers the overall system performance and identifies resilience attributes already present and, additionally, any gaps or shortfalls in resilience. (UKWIR 2013)

Vulnerability Susceptibility to damage or perturbation.

WLC

Whole life costing. Definition taken from BS/ISO 15686. A methodology for systematic economic consideration of all whole-life costs and benefits over a period of analysis, as defined in the agreed scope

NOTE 1 The projected costs or benefits may include external costs (including, for example, finance, business costs, income from land sale, user costs).

NOTE 2 Whole-life costing can address a period of analysis that covers the entire life cycle or (a) selected stage(s) or periods of interest thereof.

Appendices

Appendix A: Stages 1 and 2

A1 Stage 1 data sheets

A1.1 Asset Management Plan subject headings to PAS55

4.1 General requirements

4.2 Asset management policy

4.3.1 Asset management strategy

4.3.2 Asset management objectives

4.3.3 Asset management plans

4.3.4 Contingency planning

4.4.1 Structure, authority and responsibilities

4.4.2 Outsourcing of asset management activities

4.4.3 Training, awareness and competence

4.4.4 Communication, participation and consultation

4.4.5 Asset management system documentation

4.4.6 Information management

4.4.7.1 Risk management processes

4.4.7.2 Risk management methodology

4.4.7.3 Risk identification and assessment

4.4.7.4 Use and maintenance of asset risk management

4.4.8 Legal and other requirements

4.4.9 Management of change

4.5.1 Life-cycle activities

4.5.2 Tools, facilities and equipment

4.6.1 Performance and condition monitoring

4.6.2 Investigation of asset-related failures, incidents and non-conformities

4.6.3 Evaluation of compliance

4.6.4 Audit

4.6.5.1 Corrective and preventative action

4.6.5.2 Continual improvement

4.6.6 Records

4.7 Management review

A1.2 Spreadsheet option for assessing asset management progress (option discarded so for illustration only)

	Asset Management Plan																					
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
description	demand analysis	strategic planning	opex evaluation	capex evaluation	asset costing and accounting	asset creation	systems engineering	maintenance delivery	resource management	incident response	asset rationalisation and disposal	asset knowledge and standards	asset information and systems	asset knowledge and data	individual competence and behaviour	organisational structure and culture	contract and supply management	risk assessment and management	sustainable development	weather and climate change	review and audit	policy and strategy
additional explanation	Input from customers	Input from regulator	whole life cost element	whole life cost element		PAS 55 life cycle activities	PAS 55 life cycle activities	PAS 55 life cycle activities			PAS 55 life cycle activities											
Map to PAS 55-2:2008 sections	0.4/fig 4	0.4/fig 4				4.5.1.3	4.5.1	4.5.1.4 and 4.5.1.5	4.4.3	4.3.4	4.5.1.4 to 4.5.1.6	4.6.6	4.4.5 and 4.4.6	4.6.6	4.4.3	4.4.1	4.4.2	4.4.7	4.4.9	4.3.4	4.6 and 4.7	4.2 and 4.3.1

A1.3 Summary of energy company maintenance guides

information			maintenance plan									primary focus of	
company	link of documents	description	inspection	how often (inspection)	replacement	financial	health and safety	renovation	audits	maintenance test	preventive	sustainability	productivity
Scottish Hydro-electric	http://www.ukace.org/publications/ACE%20Research%20%282001-12%29%20-%20Directory%20of%20Energy%20Services%20for%20Housing%20Associations%20%5BHandbook%5D	Document about Scottish hydro-electric, including a little on maintenance (in particular replacement and renovation)	x		x			x					x
Scottish Power	http://www.google.com/search?q=asset+management+uk+energy&ie=utf-8&oe=utf-8&aq=t&rls=org.mozilla:fr:official&client=firefox-a#sclient=psy&hl=fr&client=firefox-a&rls=org.mozilla:fr%3Aofficial&source=hp&q=%22mainten	Annual report including economics, management and maintenance				x	x		x			x	
Nuclear company	http://www-pub.iaea.org/MTCD/publications/PDF/te_1590_web.pdf	Report of ILS in nuclear company, including maintenance solutions	x				x			x	x	x	
National Grid	http://www.nationalgrid.com/uk/Gas/OperationalInfo/maintenance/	Maintenance plan National Grid	x					x		x		x	
Western power distribution	http://www.google.fr/#sclient=psy&hl=fr&source=hp&q=maintenance+plan+western+power+distibution&aq=f&aqi=&	Electrical maintenance	x		x		x					x	

The maintenance plan sub headings were derived on a heuristic basis, i.e. from a reading of the documents.

A1.4 Infrastructure sector asset management

Energy sector		Companies		Relevant docs
Electricity and Gas		Ofgem		http://www.ofgem.gov.uk/Licensing/Work/Pages/Work.aspx
				http://www.ofgem.gov.uk/Licensing/Work/Documents1/LicAppGuidance011008.pdf
				http://www.ofgem.gov.uk/About%20us/CorpPlan/Documents1/Corporate%20Strategy%20and%20Plan%202010-2015.pdf
				http://www.decc.gov.uk/en/content/cms/legislation/white_papers/emr_wp_2011/emr_wp_2011.aspx
				2011 elec reform-white-paper-exec-summary
				Energy ownership database on Ofgem website
		Scottish and Southern Energy		
		Scottish Power		
		EON		
		EDF		
		Centrica		
		National Grid		
Oil		BP		
		Shell		
		Cairn Energy		
Nuclear		EDF		
				http://www.nuclearsupplychain.com/
Wave/wind		Iberdrola/Scottish Power		Andrawus thesis, Robert Gordons University

Transport sector		Companies		Relevant docs
Highways				
		Transport Scotland		http://www.audit-scotland.gov.uk/media/article.php?id=164
				http://www.scotland.gov.uk/Publications/2005/01/20548/50337
		Dundee City Council		City Development Department Service Plan 2010-2012; from website
				Local transport Strategy October 2000; from website
		Highways Agency		http://www.highways.gov.uk/aboutus/30779.aspx
		England and Wales		http://www.ukroadsliaisongroup.org/pdfs/090423%20-%20life-cycle%20planning%20doc.pdf
		General		http://www.ukroadsliaisongroup.org/pdfs/060202%20-%20Highway%20Asset%20Management%20Framework.pdf
				http://www.performance-based-road-contracts.com/documents.htm
		Leeds city council		http://helg.org/admin/wp-content/uploads/Leeds-Asset-Management-Case-Study.pdf
		Herts county council		http://www.hertsdirect.org/infobase/docs/pdfstore/ltp2annexd.pdf
				http://www.hertsdirect.org/services/transtreets/transplan/ltp/LTP3/ltp3docs/
Rail		Network Rail		rvfm-atkins-asset-management-250511
				nr_efficiency_assessment_0910.pdf
				rvfm-first-economics-asset-ownership-211210.pdf
				http://www.rail-reg.gov.uk/server/show/nav.2295
				http://www.rail-reg.gov.uk/server/show/nav.147
Air		BAA		http://www.baa.com/portal/page/Investor/BAA+Airports%5EInvestor+centre%5EDocument+centre%5ECapital+investment+plans%5EHeathrow+CIP+2011/daf0e85abc790310VgnVCM10000036821c0a____/448c6a4c7f1b0010VgnVCM200000357e120a____/%20centre
		Manchester Airport		http://www.manchesterairport.co.uk/manweb.nsf/All+Content/currentannualreport
				http://www.manchesterairport.co.uk/manweb.nsf/alldocs/10F56C819A51454E8025739300388C1D/$File/Masterplan.pdf
Waterways		BWB		http://www.britishwaterways.co.uk/our-work/maintenance-and-improvement/customer-service-standards
				http://www.britishwaterways.co.uk/media/documents/cop_2011.pdf
				http://www.britishwaterways.co.uk/media/documents/Waterways_2025.pdf
				http://www.britishwaterways.co.uk/media/documents/Annual_Report_and_Accounts_2009-10.pdf
Ports		Forth Ports		http://www.halcrow.com/portal/default.asp

Water sector companies		Relevant docs
Scottish Water		http://www.scottishwater.co.uk/portal/page/portal/SWE_PGP_NEWS/NEWS_JUN11/NEWS_JUN11_ANN_REP/ScottishWaterAnnualReportAccounts201011.pdf
		http://www.scottishwater.co.uk/portal/page/portal/SW_PAGE_GROUP_PS_ADMIN/SW_PUB_SCHEME_ADMIN_HOLDING/TAB65572/DELIVERY%20PLAN%20-%20MAY%202006.pdf
		http://www.scottishwater.co.uk/portal/page/portal/SWE_PGP_NEWS/SWE_PGE_NEWS/INFO_CLIM_CHANGE/Scottish_Water_Carbon_Plan_2010.pdf
		http://www.scottishwater.co.uk/portal/page/portal/SW_PAGE_GROUP_PS_ADMIN/SW_PUB_SCHEME_ADMIN_HOLDING/TAB65572/SecondDraftBusinessPlanMarch09.pdf
		http://www.scottishwater.co.uk/portal/page/portal/SW_PAGE_GROUP_PS_ADMIN/SW_PUB_SCHEME_ADMIN_HOLDING/TAB65572/National%20Sludge%20Strategy.pdf
		http://www.scottishwater.co.uk/portal/page/portal/SW_PAGE_GROUP_PS_ADMIN/SW_PUB_SCHEME_ADMIN_HOLDING/TAB65572/Adopted%20WRP09%20Summary%20Document.pdf
		http://www.scottishwater.co.uk/portal/page/portal/SW_PAGE_GROUP_PS_ADMIN/SW_PUB_SCHEME_ADMIN_HOLDING/TAB65572/SecondDraftBusinessPlanAppendicesMarch09.pdf
		http://www.scottishwater.co.uk/portal/page/portal/SW_PAGE_GROUP_PS_ADMIN/SW_PUB_SCHEME_ADMIN_HOLDING/TAB65572/201011DeliveryPlanUpdate.pdf
		http://www.scottishwater.co.uk/portal/page/portal/SWE_PGP_PUBLICATIONS/SWE_PGE_PUBLICATIONS/SWE_2_PUB_FOI_SEA/PUB_REP_SEC_DRAFT_BUS_PLAN
		http://www.watercommission.co.uk/UserFiles/Documents/WICSPerformanceReport2010.pdf
		http://www.watercommission.co.uk/default.aspx?VirtualHandlerName=Business_Plan_Guidance
Ofwat		http://www.ofwat.gov.uk/pricereview/pr09phase2/pr09phase2letters/ltr_pr0923_amabaselinesetting
		http://www.ofwat.gov.uk/publications/pricereviewletters/ltr_pr0932_capmaintex
		http://www.ofwat.gov.uk/publications/pricereviewletters/ltr_pr0932_capmaintex_appendix.pdf
		http://www.ofwat.gov.uk/regulating/ltr_md212_assetmngplan
		http://www.ofwat.gov.uk/publications/pricereviewletters/ltr_pr0938_serviceability
		http://www.ofwat.gov.uk/publications/pricereviewletters/ltr_pr0937_ama
		http://www.ofwat.gov.uk/publications/pricereviewletters/ltr_pr0937_appa.pdf
		http://www.ofwat.gov.uk/pricereview/pr09phase3/sub_fbp_pr09partasumm
		http://www.ofwat.gov.uk/pricereview/sds/
		http://www.ofwat.gov.uk/aboutofwat/structure/boardmeetings/min_obm20110616.pdf
England and Wales water companies		http://www.anglianwater.co.uk/_assets/media/strategic-direction-statement.pdf
		http://www.anglianwater.co.uk/about-us/statutory-reports/EF4060AF6BE345CE9F73F7F86158824C.aspx
		http://www.unitedutilities.com/Documents/strategicdirectionstatement.pdf
		http://www.unitedutilities.com/PR09FinalBusinessPlan.aspx
		http://www.nwl.co.uk/nwlookingtothefuture.aspx
		http://www.nwl.co.uk/finalbusinessplan.aspx
		http://www.stwater.co.uk/upload/pdf/Focus_on_water_pdf_for_website_FINAL_14_DECEMBER.pdf
		http://www.stwater.co.uk/server.php?show=nav.6408
		http://www.thameswater.co.uk/cps/rde/xchg/corp/hs.xsl/6759.htm
		http://www.thameswater.co.uk/cps/rde/xchg/corp/hs.xsl/6759.htm
		http://www.southernwater.co.uk/Aboutus/library/strategicDirectionStatement.asp
		http://www.southernwater.co.uk/Aboutus/library/businessPlan.asp
		http://www.yorkshirewater.com/medialibrary/PDF%20files/Strategic_Direction_Statement.pdf
		http://www.yorkshirewater.com/pr09
		http://www.dwrcymru.com/English/Company/dwrcymru/SDS/index.asp
		http://www.dwrcymru.com/English/library/Reports/companyreports/investmentplans/index.asp

		Companies	Regulated Private Companies?	Research back up centres	Regulator details	Regulator website	Relevant docs	Description	People
Utility sector structure and contacts									
Telecoms	BT	BT	Yes		Ofcom				
	Cable	Virgin	Yes						
IT									
Waste	Private companies	Biffa	Yes						
		(zero waste scotland)	No						
		Viridor					http://www.viridor.co.uk/		
		Greater Manchester					http://www.gmwda.gov.uk/		
Resilience							http://thisbigcity.net/the-bionic-city-a-natural-blueprint-for-future-cities/	Bionic cities	

A2 Stage 2 data sheets

A2.1 Asset Management Plan comparisons

Findings under each heading are underlined.

A2.1.1 Anglian Water

Business Plan 2010-2015

http://www.anglianwater.co.uk/about-us/statutory-reports/EF4060AF6BE345CE9F73F7F86158824C.aspx

AMP subject headings to PAS55

4.1 General requirements

Define and document the scope of the system

Control of outsourcing

Scope largely controlled by Ofwat questions/requirements, aided by reporter scrutiny. Scope includes all the regulated elements of the business – little opportunity to scale it up to include wider responsibilities. B3,3.0.33 – Anglian rated highest by Ofwat in 2008. Outsourcing partners – see B3, 3.0.106.

4.2 Asset management policy

B1 shows an impressive level of analysis of customer affordability. No specifics seen on policy – likely to be in higher level documents.

4.3.1 Asset management strategy

Strategic direction statement covers this. Strategy includes metering etc. Strategic direction statement includes details on climate change, resilience and innovation. B1 also looks at future issues which may impact upon plans. Projected population increases, fewer people per household, immediate recessionary pressures, ageing population, climate change, carbon limits, rising expectations, rising environmental standards, diffuse pollution, 1st time sewerage connections, increasing bad debt. B3 page 23/24 also covers it.

4.3.2 Asset management objectives

B2 shows increasing productivity evidence. B2/2.1.13. B3/3.0.11 service levels to be maintained, not increased. Risk levels also to be maintained. Business objective shown on B3, 3.0.102 – least cost option to maintain service levels.

4.3.3 Asset management plans

Page B3 page 6 lists the key points – impressive range of deterioration, risk and financial models are in use, validated against actual problems and claimed to be statistically accurate. Overall 6 stage approach shown on B3, 3.0.34.

4.3.4 Contingency planning

B1 looks at the post 2010 environment. The capital maintenance investment programme is based on an assessment of operational risks. B3 page 6 allows for resilience and redundancy. B3 page 31 allows for future housing plans.

4.4.1 Structure, authority and responsibilities

B1, 1.3. B3 page 24 – PR0-9 executive group meet fortnightly. Individual reviews are held to make responsibilities clear (B3 3.0.58). Job role outlines (3.0.59) are used. Capital spend management detailed in 3.0.105

4.4.2 Outsourcing of asset management activities

B3 3.0.86 – cost consultants. 3.0.106. Ernst and Young 3.5.18. IT support 3.5.27

4.4.3 Training, awareness and competence

3.0.108 details briefly. Skills and behaviours framework and personal development plans. Not a lot of detail here though.

4.4.4 Communication, participation and consultation

B1, 1.4.36-1.4.39 summarise customer consultation and priorities arising. B3 page 23/24 show customer surveys. Overall policy of not increasing or reducing service levels is based on extensive customer feedback.

4.4.5 Asset management system documentation

In a sense the business plan fulfils most of this requirement – any further AMP data is not accessible to us.

4.4.6 Information management

B3, page 6 – SAP asset hierarchy records. Not possible to access systems directly. C3 covers asset inventory.

4.4.7.1 Risk management processes

B1, 1.3 lists risks; high and low level. B3, page 6 lists models. B3 page 11 shows that investment is targeted at equipment of most benefit to customers. They have a service measure framework. They employ site surveys to back up their modelling.

4.4.7.2 Risk management methodology

B3, page 6 includes 17 different pipe deterioration models, service impact modelling covering 81,000 km of pipes and 6155 sites. Service failure probability measures. B3 page 9 states the use of modelling for future water main bursts; allowing the targeting of pipes at greatest risk. B3 3.0.61 shows a separation of failure and service failures. B3 page 28 gives more detail.

4.4.7.3 Risk identification and assessment

B1, 1.3 lists risks, high and low level. B3, page 6 lists probability based risk models as a basis for the capital budget. B3 page 11 – economic replacement point model for water meters of 13 years. B3 page 27 shows risk definition – includes an element for social costs. Deterioration is measured by evolutionary polynomial regression modelling.

4.4.7.4 Use and maintenance of asset risk management

B3, page 6 lists models. B3 page 30/31 shows an objective of an optimised capital plan. The optimisation is reached by iteration, not by use of an optimisation tool.

4.4.8 Legal and other requirements

B1 is strong on financial risks and the impact of future legislation.

4.4.9 Management of change

B1 anticipates future changes and identifies whether they have been allowed for in budgets.

4.5.1 Life-cycle activities

B3, 3.0.91 – whole life costing basis.

4.5.2 Tools, facilities and equipment

In a sense this is the above ground, non-infrastructure works; so is covered under other general headings.

4.6.1 Performance and condition monitoring

B3, page 6 shows that risk models are correlated with actual failure records. B3 3.0.77 and 3.0.80 link deterioration curves with service impact models.

4.6.2 Investigation of asset-related failures, incidents and non-conformities

These are fed back into the deterioration models to make them robust.

4.6.3 Evaluation of compliance (with legal and regulatory requirements)

The whole business plan is evidence of this; in terms of meeting regulatory requirements; and other legal constraints, e.g. water framework directive, are included. 3.0.109 – trying for ISO 9001.

4.6.4 Audit

3.0.111 mentions validation of the investment plans. 3.0.114 mentions the reporters view. 3.1.2.32 mentions financial auditors.

4.6.5.1 Corrective and preventative action

3.1.2.37 – planned preventative maintenance being done – flushing of water mains. 3.1.2.38 – water main bursts expected to be constant.

4.6.5.2 Continual improvement

B1 shows evidence of continuing improvement of standards. 3.0.110 states that AWS are committed to it. 3.1.2.44 – unit cost reviews.

4.6.6 Records

B3, page 6 mentions 300,000 items of equipment and 6155 separate sites. They use SAP ALM for non infra assets and a GIS background for infra assets. These come together in Asset plus (3.0.73) for a risk based investment plan. Further described in doc C3.

4.7 Management review

There are refs to the control arrangements for monitoring spend and progress but I can't find refs to less frequent, major, reviews.

A2.1.2 Hertfordshire County Council

Transport Asset Management Plan

Draft 1.2 October 2008

(saved in task 1; dropbox)

AMP subject headings to PAS55

4.1 General requirements

Define and document the scope of the system

Control of outsourcing

1st authority to produce a HAMP (Highways AMP); now developed into a TAMP (Transport AMP). There are annual reports to the highway committee but no evidence of intermediate plan updates. 1.5 - role of the TAMP is to reflect strategic goals in the operation plans (essentially a linking vehicle). P35 mentions the intention to produce a more detailed level 2 document (therefore this one is 'high level' only). Can't find the level 2 document. Overall impression is that they've brought a consultant in to produce the HAMP but it's difficult to see how deeply rooted the thinking has become since then.

4.2 Asset management policy

1.4 – policies and procedures are listed elsewhere. 3.1 shows origin of AM principles.

4.3.1 Asset management strategy

1.5 – strategic goals are listed elsewhere; other docs are referenced.

4.3.2 Asset management objectives

1.3 – core role of the plan is to encourage good decision making. Also refers to corporate objectives stated in the corporate plan and the local transport plan. 1.8.3 lists 6 principles which guide the objectives. 1.9 lists the planned outcomes. 3.3 reiterate the 6 principles but they seem to be saying that AMP proposals cannot be ‘smart’ – the level of non-specificity is indicative of a lack of detailed work (and understanding)?

4.3.3 Asset management plans

1.7 – intention is to create an evolving statement of practice. 3 levels of info – think we can only find level 1. 4.1 gives a 4 stage process for generic asset management planning.

4.3.4 Contingency planning

1.8.2 – lists future demands and acknowledges the need for flexibility.

4.4.1 Structure, authority and responsibilities

Some indication of the decision making process/structure (p32) but no link to manpower organisation. No detailed indication that there is a high level drive to make the case for pushing the AMP thinking forward.

4.4.2 Outsourcing of asset management activities

Page 26 – works programme is delivered by a highways partnership and other specialist contracts.

4.4.3 Training, awareness and competence

Good call handling and customer service standards (p33) is cited as assisting service delivery – but there’s not much on disseminating asset management practice across the workforce. Co-located teams also cited as important.

4.4.4 Communication, participation and consultation

1.9.1 describes ongoing improvement. Plan to be kept on the council intranet site. P15 – MORI survey of customer concerns – used to set corporate priorities. Detailed carriageway sheets – use customer surveys.

4.4.5 Asset management system documentation

There is the draft plan; annual reports on progress; all on the intranet site. P35 shows an intention to produce a more detailed level 2 plan – ideally this is what we should be assessing against but it doesn’t exist yet.

4.4.6 Information management

P30 – carriageway inventory and condition data is used to give an optimised works programme and future projections. Factors for ranking of footway and drainage schemes are listed. P37 starts listing quantities. P36 lists examples from 6 sector asset group summaries. Detailed sector sheets give some indication of gaps in data storage – i.e. little data on drainage or footway condition.

4.4.7.1 Risk management processes

1.6 – they use pavement deterioration modelling. 1.8.4 has 4 processes. 3.3 – actions will balance cost, service standard and risk – they ought to be aiming for meeting service standards at minimum cost and acceptable risk?

4.4.7.2 Risk management methodology

1.8.4 – first mention of risk as a decision making influence. Page 29 – gives an aspiration of using methodologies to set optimum investment levels – i.e. budgets. Implication is that they are not at that stage yet. Weighted matrices are used. P30 – carriageway deterioration modelling is used.

4.4.7.3 Risk identification and assessment

Only clues are in the detailed sector sheets at the back – and that isn't much.

4.4.7.4 Use and maintenance of asset risk management

1.9 lists the planned outcomes. P32 – integrated works programme is the output (planned up to 5 years ahead) but it's not clear in what way good asset management improves this process.

4.4.8 Legal and other requirements

Government guidance and other legal controls are mentioned as external factors.

4.4.9 Management of change

1.6 – achievements to date are listed. 1.9.1 – organic additions.

4.5.1 Life-cycle activities

P29 – option appraisal needs to demonstrate 'long term value for money'. P31 is specific on the need to minimise whole life costs. P36 – there are some asset lifecycle plans, but others need to be developed. Carriageway sheets – looking to use a WLC viewpoint.

4.5.2 Tools, facilities and equipment

No data, apart from refs to national surveys of carriageway condition.

4.6.1 Performance and condition monitoring

1.8.4 – 4th process. Also mentioned (outline only) on page 26. 4.6 goes through the detail – measuring outcomes rather than outputs. P35 lists the reporting vehicles. Performance indicators to be reviewed but they are not listed in detail. More data in the sector sheets at the back – emphasis is more on the improvements needed to data capture systems.

4.6.2 Investigation of asset-related failures, incidents and non-conformities

P30 includes the use of repair history and the claims history. Sector sheets have some info – e.g. bridge parapet surveys.

4.6.3 Evaluation of compliance (with legal and regulatory requirements)

Some refs in the sector sheets – e.g. refs to new indicator systems for structures – but they are not comprehensive, only examples.

4.6.4 Audit

No info.

4.6.5.1 Corrective and preventative action

Clues to data improvements needed in the sector sheets – other than that; no procedures listed.

4.6.5.2 Continual improvement

P31 – recognition of the need to combine work items to avoid causing congestion every time. P33 – improvements from the highways strategic alliance to be fed back into future arrangements. Sector sheets – gap analysis examples are given.

4.6.6 Records

Not mentioned.

4.7 Management review

1.9.1 - no end date or specific review dates.

A2.1.3

Scottish Water

Delivery Plan 2010-2015, published March 2010.

AMP subject headings to PAS55

4.1 General requirements

Define and document the scope of the system

Control of outsourcing

There is no asset management plan as such. Secondary documents state that SW reckon they have most of the building blocks in place but they just haven't pulled it all together into one document. 20% of the capital programme due to be delivered by SW solutions 2 (P37/38). P40 – they want to go for PAS 55 accreditation.

4.2 Asset management policy

Section 2 - 6 aspirational pillars as part of their vision. Section 3 gives some customer opinions.

4.3.1 Asset management strategy

Section3 – minister's direction is to achieve upper quartile performance in relation to the English and Welsh companies. They also (P12) want to stay in front of the demand curve, but not commit to specific assets until developers are committed.

4.3.2 Asset management objectives

Section 3 - Minister's directions – upper quartile performance, plus a table of objectives showing improvements expected between 2010 and 2015. These include low pressure, malodours, sewer flooding, water quality (particularly crypto eradication). Demand management options are to be examined (note – only examined). Much of this programme is driven by EU legislation or remedial works.

4.3.3 Asset management plans

None available but it could be argued that, like the English and Welsh companies, the delivery/business plan fulfils this role.

4.3.4 Contingency planning

P18 – security service standards in case of drought. Need to access the OPA measurement of security of supply. There is a quantified index. P24 flood protection works are planned (risks have been surveyed). Some mention of demand management like leakage control. P25 – aim to make network resilient to climate change. UKCIP 09 mentioned. Water metering trials being undertaken (P26)

4.4.1 Structure, authority and responsibilities

No structure or names are given.

4.4.2 Outsourcing of asset management activities

Design and construction partners will be expected to conform to company systems. P37 mentions SW solutions II will deliver around 20% of the capital schemes.

4.4.3 Training, awareness and competence

3.0.108

4.4.4 Communication, participation and consultation

Page 9 – complaint monitoring and customer questionnaires are used to set customer target service levels. They also consult with licensed providers and developers. P39 – PACE programme plus new intelligent control centre.

4.4.5 Asset management system documentation

P39 – business change programme in place called DRIVE

4.4.6 Information management

P40 – new capital investment system and processes (CISP project).

4.4.7.1 Risk management processes

For the investment risks, there is a contingency fund, to be managed by a 7 stage process, and overseen by a board.

4.4.7.2 Risk management methodology

B3, page

4.4.7.3 Risk identification and assessment

Section 9 lists main commercial risks to the capital programme plus other investment uncertainties. Some mitigation measures are described.

4.4.7.4 Use and maintenance of asset risk management

Nothing this detailed is included.

4.4.8 Legal and other requirements

Minister's directions have a legal basis?

4.4.9 Management of change

P32 – forecast priorities beyond 2015. Intention to undertake studies 2010-15 so that info is available to set and cost priorities for the following term. Begs the question of who determines the study topics? Some are included in ministerial directions but are all of them?

4.5.1 Life-cycle activities

Whole life cost analysis of Dalmuir options – p39. P46 etcetera, cash flow statement – what's the basis for valuation of assets? Table 8.14 for example – what's the calculation behind depreciation charges?

4.5.2 Tools, facilities and equipment

P35 – they have drainage models covering 85% of the population.

4.6.1 Performance and condition monitoring

P35 – infiltration studies are planned.

4.6.2 Investigation of asset-related failures, incidents and non-conformities

Nothing mentioned.

4.6.3 Evaluation of compliance (with legal and regulatory requirements)

Much of the report details how ministerial objectives will be met but not the process or principles which underlie the objectives. Some mention made of DWQR and SEPA.

4.6.4 Audit

No audit mentioned (but there must be?).

4.6.5.1 Corrective and preventative action

Section 10 describes monitoring performance – outcomes, outputs and inputs.

4.6.5.2 Continual improvement

P27 – looking at increasing electricity and heat generation from their sites. P38 – now clustering and sequencing work programmes and looking too avoid the national peak resource demand. Looking also to develop a whole life costing tool to include carbon use.

4.6.6 Records

Nothing described in detail.

4.7 Management review

There is a seven stage process to spend/monitor spend on issues which have not been fully investigated yet. Water industry commission monitor the overall measure of delivery (OMD) – there are working and monitoring groups (P56). Table 10.6 summarises the work programme.

A2.1.4

South Yorkshire local transport plan partnership

South Yorkshire Highway Asset Management Plan September 2010

AMP subject headings to PAS55

4.1 General requirements

Define and document the scope of the system

Control of outsourcing

Exec summary – scope covers road assets only, and at a generic level. There will be separate transport asset management plans and local transport plans. Note the 'HAMP' is broadly based on the County Surveyors' Society Framework document. Note 2.1.8 – focuses on level of service rather than the system itself. 2.1.7 – list of included assets. Note this HAMP is due to be superseded by a TAMP (Transport AMP) by March 2011 (2.4.3). 2.4.4 deals in a limited way with capital improvements. 2.4.5 lists other relevant docs. 2.8 includes rights of ways. One

4.2 Asset management policy

No over-riding policy statement included but 2.3.1 discusses seeking to optimise asset value over their whole life. 2.4.5 lists the other policy documents. half

4.3.1 Asset management strategy

2.5 local transport plan may include strategy, certainly 4 themes are listed. half

4.3.2 Asset management objectives

1.11 – more work to be done in defining service levels. Improvement action plans will be local authority specific and will drive continuous improvement of service delivery. 2.6 – high level objectives come from the local transport plan. 2.7 – wish to improve co-ordination with street works activities by utilities. Improvement plans listed in section 8. half

4.3.3 Asset management plans

This is the first one therefore needs development. half

4.3.4 Contingency planning

Not specifically mentioned, other than climate change as a risk. Probably included in an emergency plan. zero

4.4.1 Structure, authority and responsibilities

This is an overarching asset plan, which includes reference to other relevant documents but doesn't mention the 'internal' set up. Therefore, no duty holders mentioned. Zero.

4.4.2 Outsourcing of asset management activities

Not specifically dealt with but work carried out over last 5 years is tabled in section 4. Future plans include PFI. zero

4.4.3 Training, awareness and competence

Nothing. zero

4.4.4 Communication, participation and consultation

External to the organisation, service levels are set by (section 3) reference to legal guides plus customer feedback through the national benchmarking group. The trans authority nature of this plan by implication requires high level co-operation but internal communication is mentioned only indirectly. zero

4.4.5 Asset management system documentation

This is an overarching asset plan, which includes reference to other relevant documents. half

4.4.6 Information management

National indicators for road condition are listed in 2.11, along with measurement tools. Winter services policy documents listed, plus road classification network lengths and a detailed hierarchy for both roads, footways and rights of way. Overall lengths/numbers for street lighting and signs are summarised in 2.18/19. Traffic signals, street furniture, structures, verges, trees, are also included. Note highway drainage and other underground assets are poorly recorded, and not even systematically inspected. 2.25.3 – each authority has, as part of their gap analysis, prioritised inventory collection. half

4.4.7.1 Risk management processes

4.4.1 summarises the prioritisation processes which each authority applies to the survey data in order to come up with a programme of works. The summary is outline only, which leaves the way open for political input into the priorities? Risks are listed later but no detailed methodology is given. half

4.4.7.2 Risk management methodology

4.4 makes clear that the maintenance is budget constrained and, further, that the method by which budgets are set is not explained – i.e. the prioritisation between sectors is not explained (probably largely political). zero

4.4.7.3 Risk identification and assessment

The national guidance docs are listed but no more detail given. Section 7 gives main outline risks to the council overall highways programme. half

4.4.7.4 Use and maintenance of asset risk management

No direct evidence of this – schemes are prioritised within the budget limits but no evidence of systematic balancing of priorities on a risk basis. zero

4.4.8 Legal and other requirements

Legal guides and documentation are mentioned. half

4.4.9 Management of change

2.2.5 An Improvement Action Plan will be published for each authority, with a three year lifecycle. Hamps will have an annual review. 7.4 shows appreciation (only?) of climate change effects. half

4.5.1 Life-cycle activities

2.3.1 and 2.3.2 confirm a life cycle approach. 6.2.1 mentions the highways efficiency toolkit which contains an asset management approach. 7.2 mentions that a WLC approach is used when comparing different treatments (but not to compare schemes in different areas?) half

4.5.2 Tools, facilities and equipment

4.4 – Scanner and scrim surveys used. half

4.6.1 Performance and condition monitoring

4.4 – Scanner and scrim surveys used along with safety and serviceability surveys. 5.2 – surveys customer feedback, internal objectives and benchmarking against other authorities.7.2 data is kept in order to evaluate best whole life cost surface treatment. 7.5 lists factors in a gap analysis carried out by each individual council. one

4.6.2 Investigation of asset-related failures, incidents and non-conformities

4.4 – Scanner and scrim surveys – no further detail. zero

4.6.3 Evaluation of compliance

5.1 and 5.2 covers it. Section 6 checks for value for money. half

4.6.4 Audit

Indicators are checked. No mention of an actual audit though. Zero.

4.6.5.1 Corrective and preventative action

List of improvement items. Some good overall sense of programme corrections following feedback. half

4.6.5.2 Continual improvement

Section 8 – includes PFI long term maintenance contract for Sheffield (only) which will encourage the provider to adopt WLC principles. one

4.6.6 Records

2.25.3 – each authority has, as part of their gap analysis, prioritised inventory collection. Section includes overall asset valuation for each authority, but isn't condition based. 2010/2011 is due to be updated according to the CIPFA report. half

4.7 Management review

The HAMP will be reviewed annually. Section 9 mentions a continuous review. One.

A2.1.5

Transport Scotland

Road asset management plan for Scottish Trunk Roads April 2007 - March 2009

AMP subject headings to PAS55

4.1 General requirements

Define and document the scope of the system

Control of outsourcing

Operating companies maintain the 4? Areas. TfS split into 5 directorates – trunk roads network management is most relevant (and produced the ramp). The plan is version 1, will be developed in time, and be used to produce a work plan and a finance plan. 3.1.5 – this RAMP only applies to roads and bridges – scope to be widened for future ramps. Website claims that a second version will be published in 2011. In general, this sets out what is proposed, without giving the detail to do it.

4.2 Asset management policy

Separate government publication – Scotland's national transport strategy sets out the vision for roads, railways, airports and ports. Government sets overall policy. Other drivers are listed in 1.4.7. 1.5.7 mentions the corporate plan and business plan. See 2.2 corporate aims.

4.3.1 Asset management strategy

1.4.11 mentions a performance management framework which is intended to measure progress – also lists immediate improvements expected. 4.4.5 mentions the national transport strategy plus corporate and business plans.

4.3.2 Asset management objectives

Exec summary – improved safety, journey reliability and more efficient use of money. Congestion caused by roadworks is an identified problem. 1.3.5 lists challenges to be met. 1.5.1 shows objectives are explained in the corporate and business plans. 2.3.1 lists objectives from other docs, only where relevant to AM. Table 3 links objectives to AM principles.

4.3.3 Asset management plans

Most up to date one is Apr 07 to Mar 09 – tends to imply that the initial motivation hasn't extended to producing an update. Embedment is mentioned in 1.4.12 – asset management improvement programme.

4.3.4 Contingency planning

7.3.8 – emergency response times are included in the OC contracts – times set by Scottish ministers.

4.4.1 Structure, authority and responsibilities

A to I 5 directorates are in place but actual AM responsibilities are not outlined. 4.2 goes into more detail, including the operating companies plus DBFO contracts. Note PAG also audits the TRNMD directorate.

4.4.2 Outsourcing of asset management activities

4 Operating companies maintain their areas – how much autonomy do they have?

4.4.3 Training, awareness and competence

4.1.4 recognises that training will be needed.

4.4.4 Communication, participation and consultation

1.4.2 mentions service levels set in consultation with customers.2.4 describes customer surveys in 2007. This is to be incorporated in the next RAMP. 4.1.6 recognises the need to filter down knowledge to the councils. 6.2.3. mentions research into links between service levels and engineering standards.

4.4.5 Asset management system documentation

Apart from the plan; largely to be considered during the AMP.page 21

4.4.6 Information management

SERIS is the name of the data management system. Section 3 gives the overall data. 3.1 – beginnings of an asset classification system. Appendix C goes into detail. 4.4.13 mentions SERIS and TRBDB. Improvements are planned under the AMIP.

4.4.7.1 Risk management processes

Section 7 - There is a corporate risk strategy and a corporate risk register. Each directorate also has a risk register.

4.4.7.2 Risk management methodology

No detail given.

4.4.7.3 Risk identification and assessment

3.2.13 highlights an ageing of the older network (presumably because funds get used on the life expired roads. Also 20% of motorways are life expired!

4.4.7.4 Use and maintenance of asset risk management

Largely left to AMIP?

4.4.8 Legal and other requirements

The current plan arose out of a 3 year asset management improvement programme, starting in May 2006.

4.4.9 Management of change

1.4.13 and section 14 lists the packages arising from the asset management improvement programme.

4.5.1 Life-cycle activities

Exec summary – life cycle plans to be developed (i.e. not done yet). Section 8 – to be developed under the AMIP. Principles seem understood but work will be ongoing for years to develop the optimal interventions. Note they use a 30 year period in keeping with other authoritative industry guidance (I’ve forgotten the ref). Computerised models to be developed. 9.1.3 – carriageway maintenance options are currently compared on a WLC basis. AMIP to consider whole life value approach (sounds like vehicle to introduce resilience!) Prioritisation dealt with by value engineering processes.

4.5.2 Tools, facilities and equipment

Section 9 – decision support tools include value engineering.

4.6.1 Performance and condition monitoring

6.3.4 references performance measures for operating companies. See ref 12. Performance targets not set yet. 7.3.2 – risk based inspection regime is proposed from the AMIP but operating companies currently working to a programme based regime.

4.6.2 Investigation of asset-related failures, incidents and non-conformities

7.3.5 – safety defects have strict response time limits on rectification. Emergency response times are stated in the OC contracts.

4.6.3 Evaluation of compliance

PAG report on operating companies.

4.6.4 Audit

PAG acts as an independent auditor.

4.6.5.1 Corrective and preventative action

5.12 acknowledges that traffic volumes influence maintenance strategy. 8.4.1 mentions feedback of better info into lifecycle plans.

4.6.5.2 Continual improvement

Next RAMP is to include a work plan and a financial plan. Due to be published in spring 2009. 4.3.3. lists the tactical level as where AM can make most difference. 4.4.3 lists the plan-do-check-act stages.10.1 – looking to move to a steady state maintenance regime which gives forward visibility to the OC's, by way of a 5 to 10 year work plan.

4.6.6 Records

No detail given

4.7 Management review

No detail given.

A2.2 Highway interviews

21st September 2011

URS Scott Wilson/Halcrow/University of Dundee

REPORT of meeting to investigate DBFO contract for M74.

1.0 **Attendees**: David Fleming of URS Scott Wilson; Eddie McDowell of Halcrow; Mohammed El-Haram and Doug Thomson of University of Dundee

2.0 Background info from URS Scott Wilson

The design, build, finance and operate contract for the A74(M) runs from junction 12 to the English border (approximately 90km). There are 90km of dual 3 lane carriageways plus hard shoulders (motorway standard). Only 30km of the 90 is new construction – the rest was 'adopted' by autolink.

Autolink Concessionaires (M6) Plc were awarded a 30 year contract in July 1997. In other words, they are 14 years into their 30 year period. The current constituent companies are John Laing and Innisfree (infrastructure investment group/PFI specialists). The original contract signatories have all been bought out. URS Scott Wilson (SW) act on behalf of Transport Scotland (TS) in reporting on the performance of Autolink. SW are paired with Halcrow, who have similar duties re the 4 operating companies. SW do not produce a similar annual report to the PAG report. There are instead monthly briefing notes to TS, and regular audits.

Autolink payment is related to traffic numbers measured at 13 points on the network (i.e. shadow tolls). This can be reduced depending on KPI performance (KPI topics are largely similar to the PAG ones). All operational risk is allocated to Autolink, along with just about all other risks – apart from inflation (which is applied to shadow toll rates) and extreme 'force majeure' events. Autolink pay lane occupation charges, which vary seasonally and between day and night.

The contract requires Autolink to hand over the works to TS at the end of the thirty years with specific residual lives (e.g. 10 years for the carriageway, 20 years for the structures – etcetera). There is a specified handback process which commences 5 years before the contract end. There are also minimum operational standards applied throughout the period – e.g. standard survey methods such as scrim and deflectometer tests are done and Autolink have to repair/restore as necessary.

Autolink are only concerned with the M74. They have no similar contracts south of the border to share knowledge and resources with.

Golden River undertake the traffic counts.

Headline differences in emphasis between Autolink and the operating companies are felt to include:
a/ Autolink maintain the carriageway drainage more frequently; recognising the potential for more significant deterioration arising from poor drainage. They generally scarify the surface layer annually and replace the filter stone/pipes every 5 or 6 years.
b/ Autolink use subcontractors for all civil engineering maintenance and accord more importance to quality/performance because poor quality (e.g. joints/waterproofing) has a direct financial cost. In contrast the operating companies have more scope to use cheaper subcontractors because problems may not become apparent until after their 5 year period is over.
c/ Landscaping and rubbish collection is given high importance due to their reputational risk, particularly as the M74 is the main gateway to Scotland. In general, the investors behind Innisfree get nervous if relationships deteriorate and penalties start being imposed therefore Autolink try to avoid defect notices etc.
d/ Autolink are not subject to public sector annual budget limits and are therefore free to resurface, for example, at appropriate times of the year – generally spring/autumn as lane rental charges are higher during the peak tourist season in summer. The 30 year period again acts as an incentive to maintain durability and quality. Operating companies may have to undertake serious maintenance in winter.

3.0 Questions and answers

3.1 Contract and reporting (answers underlined)

Can we have/see a copy? There are two thick volumes, much of which includes financial info, which will be commercially sensitive. DF suggest schedule 2 would cover most of the issues we are interested in – would need TS permission to release.

Method specification or results specification? Combination of both, but based on standard Department of Transport specification.

How much latitude do autolink have to vary maintenance on a risk assessed needs basis? Generally, inspection intervals are fixed and resulting maintenance needs are driven by the minimum specified condition standards. Autolink have the freedom to concentrate more on preventive maintenance if they consider this is in their best long term interests. Category 1 defects will have time limits for repair. Defects reported in road safety audits will need rectification.

Do maintenance time limits allow for resource sharing/transfer from south of the border? Not applicable as Autolink have no other responsibilities.

What are the performance indicators and how often are they measured? (again in terms of what latitude do autolink have to vary their maintenance regime?) KPI schedule to be supplied but monitoring/measuring performance is continuous and detailed. There is some 'freeboard' between a reduction in KPI scores and financial penalties (to the extent that no financial penalties have as yet been applied).

Are HGV's rather than total vehicles given prominence in payment terms? (having more cost impacts on maintenance) Yes – there are two rates for shadow tolls – HGV's and others. The rates also increase annually with inflation and mid-term to allow for carriageway reconstruction.

Are minimum standards based on service levels; themselves based on 'customer' feedback? Standards are based on the DOT spec. Customer feedback registers as specific complaints.

Are there only penalty limits (a stick) or is there a carrot as well? No carrot. The agreement can be varied if either party proposes a change with an associated financial trade off; which is then agreed by the other party. Many of the risks are transferred directly to subcontractors.

3.2 Operation and construction

Comparison with operating companies – are they organised differently? See headline differences in section 2. – are resources less/more? Autolink have 26 directly employed operatives who staff winter protection operations (8 snowploughs) and landscaping for the rest of the year. – are improvements visible from year to year? After 14 years autolink are now on steady state maintenance operations – a routine has been established. How are learning points captured? Through the monthly reports and by addressing customer complaints.

Were initial design standards beefed up to minimise future maintenance? Only 30km was new construction and Autolink used stone mastic asphalt (SMA) in one of their first UK applications. The 60km remaining length was hot rolled asphalt (HRA). Due to errors made in the laying of the SMA this is now having to be reconstructed therefore there was an attempt at innovation but they are reverting to HRA for the reconstruction. Autolink chose to omit crossovers from the new, central 30km because they were available on the other 60km stretches.

Do autolink share resources with the M6? N/A

Any condition based maintenance? (rather than time based) Inspection intervals are specified. Maintenance needs arising from these inspections are condition based.

Any variation in carriageway construction standards along the route? Why? – and does this affect maintenance input? Only the SMA/HRA split as above.

3.3 Risk

What's the risk allocation profile between contractor and client? The contractor carries the vast majority of risks. The client increases the shadow toll rates in line with Baxter indices. The client is not allowed to construct a rival route which might pull traffic away from the M74.

Who carries the risk of extreme natural events (beyond normal design standards) Autolink

Who deals with major emergency plans? Autolink (also deal with abnormal loads) Is the performance of the emergency services (in terms of carriageway availability) a client risk? No – and autolink lose revenue whenever the motorway is closed. There is no 'social cost' penalty for road closures though.

3.4 Cost

Are life cycle costs as forecast? No detailed info but SMA problem is cancelled out by lower than expected costs on the other 60km. Certainly there are no signs of financial stress impacting on maintenance regimes.

Are deterioration curves being updated? DF has no access.

Is anyone comparing overall costs between operating companies and autolink? – are they directly comparable? Not to our knowledge. The DBFO contract would have been subject to public sector comparator limits but we have no idea if anyone in TS is monitoring comparative costs per km in relation to the operating companies. In terms of resources employed we may be able to compare resources/staffing between operating companies and autolink.

Does the shadow toll bear a linear relationship to payment? There are two rates (HGV/other) and the rate varies with inflation and also halfway through the period.

Is payment based on shadow tolls not just a source of financial uncertainty for both parties? The HGV element impacts on maintenance costs.

3.5 Asset management

Do autolink have an asset management plan? – accredited to PAS 55? No and no. They will have some elements of a plan but not in its entirety – largely due to the contract being 14 years old. DF has no visibility of initial assumptions of design lives.

In terms of resilience, is there any priority given to availability of carriageway lengths/structures where there isn't a viable diversion route? N/A as there is a parallel local distributor throughout the 90km length - suitable for short term use only.

4.0 Actions arising

DT to circulate note of meeting.

DF to forward list of autolink KPI's

Schedule 2 of the Transport Scotland/autolink contract – EM to ask permission from TS to make available.

DF to forward autolink staff organogram (for use in comparing staffing levels with the operating companies)

DF to forward example of monthly report from John Burns of autolink (subject to TS approval –EM to request permission)

Can we dig out data to investigate any relationship between surfacing/reconstruction seasonal timings and subsequent durability? This would require agreement from TS and autolink. EM and DF to inquire.

DT/EM to carry out a similar question/answer exercise on the operating companies.

5.0 Possible comparators to be investigated (between autolink and operating companies)

a/ Total annual cost to Transport Scotland per lane kilometre (or square metre of road surface).

b/ Staff resources employed per lane kilometre or square metre.

c/ Winter gritting capability in terms of gritters employed per lane kilometre or square metre.

Appendix B: Stage 3 (refer to Volume 2)